

Auditory Spatial Perception: Auditory Localization

by Tomasz R. Letowski and Szymon T. Letowski

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14. ABSTRACT Research into human auditory localization acuity and factors that compromise this acuity is an ongoing research program at the U.S. Army Research Laboratory. Although there is a wealth of information in the professional literature about the physical, physiological, and psychological underpinnings of auditory localization, the specific theoretical concepts, localization error metrics, and data collection methodologies found in various books and articles are quite diverse and frequently poorly described, making generalizations and data comparison quite difficult. This report is intended to provide information needed to clarify potential methodological and interpretational issues as well as to describe the state of the art in auditory localization science. The specific issues addressed by the report are (1) a common terminological and methodological framework for information exchange regarding localization acuity, (2) the current state of knowledge regarding human localization ability, and (3) various types of localization tasks, measures of localization accuracy and precision, and methods for handling reversal errors. Due to the angular (directional) nature of localization data, a particular focus of the report is the discussion of both circular (spherical) and linear metrics; the statistical methods of data analysis; and the criteria under which a linear analysis of localization data is justified.					
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1. Introduction

Spatial awareness is the awareness of the surrounding space and the location and position of our own body within it. Thus, it is the multisensory awareness of being immersed in a specific real or virtual environment. The surrounding environment may be static or dynamic.¹ In a dynamic environment, changes in the environment may result from movements of surrounding objects, the observer, or both. Awareness of the dynamic changes in the environment may also change as a result of the duration of exposure, a global change in the environmental conditions (e.g., amount of lighting), or changes in the physiological or psychological status of the observer. This awareness is not an on-or-off phenomenon, and its extent can be assessed by its completeness and how well it matches the actual physical or virtual environment. However, since awareness is a perceptual phenomenon, its correspondence to the physical or virtual environment is not always casual and must be considered carefully. The physical environment may include misleading or confusing clues, or its synthetic realization (virtual reality) may be flawed. Certain real properties of the environment may not be generally perceived as they truly are, e.g.,vection illusion. Therefore, the assessment of spatial awareness must take into account both the absolute physical reality and the statistical (perceptual) reality based on commonality of experience.

Spatial awareness resulting from auditory stimulation is commonly referred to as *auditory spatial awareness*. Auditory spatial awareness is the awareness of the presence, distribution, and interaction of sound sources in the surrounding space. It is an element of spatial awareness and auditory awareness, which also includes sound source detection and acoustic signal recognition. The extent of auditory spatial awareness in a given environment depends on the physiological status of the listener's sense of hearing, their auditory experience, knowledge of listening strategies, familiarity with the surrounding environment, and degree of involvement in the listening activity (motivation, attention, tiredness, etc.). It also depends on the type and extent of protective headgear worn by the individual.

Auditory spatial awareness is a three-dimensional (3-D) ability; hearing is the only directional human telereceptor that operates in a full 360° range and is equally effective in darkness as in bright light. Thus, the auditory system is frequently a guiding system for vision in determining the exact location and visual properties of a given object. Simple reaction time (SRT) to auditory stimuli is also shorter than that to other sensory stimuli (e.g., visual stimuli). Auditory SRTs are typically on the order of 100–160 ms, whereas visual SRTs are in the 200–250 ms range (Carterette, 1989, p. 91). Similarly, Welch and Warren (1986) listed auditory SRTs as

¹Ericson et al. (1991) reported choice reaction time (CRT) for an auditory localization task on the order of 3.0–3.5 s (broadband stimuli arriving from any spherical angle). Slightly longer times of 4.0–4.5 s were reported by both Ericson et al. (1991) and Endsley and Rosiles (1995) for auditory virtual reality scenarios. Noble and Gates (1985) observed that the use of hearing protectors increased localization CRT of their subjects from 3.0 s to 5.0 s.

30–40 ms shorter than visual SRTs. In fact, superior temporal discrimination is the main asset of the auditory sense (Kramer, 1994), and the human ability to discern short-term changes in arriving sound makes auditory spatial perception an important means for detecting early warning signs.

Auditory spatial awareness results from human abilities to identify the direction from which a sound is coming from, estimate the distance to the sound source, and assess the size and character of the surrounding physical space affecting sound propagation. It also includes the awareness of the presence of ambient sounds whose physical sources cannot be localized. The first three elements of auditory spatial awareness are commonly referred to in the psychoacoustic literature as the acts of auditory localization, auditory distance estimation, and auditory spaciousness assessment.

The above concept of auditory spatial awareness separates the judgment of auditory distance from the act of auditory localization. This concept differs from the concept of localization expressed in the general literature, where localization is defined as the act, process, or ability of identifying the physical location of an object—or the origin of a given activity—in space (e.g., APA, 2007; Houghton Mifflin, 2007). In the case of Euclidean space with polar coordinates, this location is specified by its azimuth, elevation, and distance. Therefore, the general definition of localization treats distance estimation as one of the elements of localization. However, it does not mean that this broad concept of localization has to be strictly followed if a different, narrow concept of localization is more operationally useful. Such a narrow interpretation of localization is frequently adopted in the psychoacoustic literature where *auditory localization* is defined as the act of identifying the direction toward the spatial location of the sound source (e.g., Illusion, 2010; Morfey, 2001; White, 1987). In these definitions, the distance to the sound source is not mentioned and its judgment is treated as a separate entity.

To avoid potential confusion between the broad and narrow meanings of the term localization, some authors (e.g., Dietz et al., 2011; Viste and Evangelista, 2003) use the term *direction of arrival* (DOA), a technical term borrowed from the fields of radar and sonar (Mathews and Zoltowski, 1994), to denote directional localization and distinguish it from general localization. Following this concept, the use of the term auditory localization would be restricted to its broad meaning. Although such an approach has some merit from the formal point of view, the term DOA is not normally used in reference to humans and may, in effect, create more rather than less confusion since the use of the narrow meaning of localization is widespread in the psychoacoustic literature. Therefore, following the narrow interpretation of the term localization, which is common in the psychoacoustic literature, the term auditory localization will be used in this report to refer solely to directional judgments.

1.1 Auditory Localization

Auditory localization is the element of auditory spatial perception that is the most critical to human effectiveness and personal safety. The sound of a weapon, vehicle, or an approaching

person can usually be heard much earlier than the source of the sound can be seen. Knowing *where* to listen improves situational awareness, speech perception, and sound source identification in the presence of other sound sources (e.g., Bronkhorst, 2000; Kidd et al., 2005). For these reasons, studies of human auditory localization performance and the localization errors made under various listening conditions are ongoing research programs in many military acoustic laboratories.

As mentioned earlier, auditory localization is a 3-D ability, but it is normally discussed in the literature as a combination of two separate judgments: a horizontal localization judgment and a vertical localization judgment. The separate focus on the horizontal and vertical judgments simplifies the discussion of the effects of the underlying localization cues. However, a number of cue-oriented and 3-D localization studies (as opposed to localization studies limited to one specific plane) have demonstrated that horizontal and vertical judgments are not fully independent and that they both depend on the actual location of the sound source in both directions.

Localization judgments can range from simple left-right, up-down, or more-less discrimination to categorical judgments to absolute identifications of specific directions in space. Two excellent sources of information on auditory localization are Blauert's (1974/2001) and Yost and Gourevitch's (1987) books on spatial hearing. Both books provide a wealth of information on the effects of signal and listening environment properties on monaural and binaural localization accuracy under various listening conditions. However, they only marginally address auditory localization metrics² and measurement methodologies. This same methodological limitation is true of most other psychoacoustic textbooks. Yet, the proper understanding of metrics and data collection methods is very important for both the collection and interpretation of auditory localization data since localization errors can be defined and measured in a variety of ways. Thus, the focus of this report is on localization metrics and data collection methodologies.

Localization judgments refer, in general, to the locations of sound sources in surrounding space; however, in some cases, the listeners may feel that the sound sources are located inside their head. Such in-the-head *imaginary (phantom) sound sources*³ are commonly perceived when sound is presented through earphones without pre-processing it using head-related transfer functions (HRTF) (see section 2.2). In addition, such sensations may exist under some open-ear conditions (e.g., Gresinger, 1998; Minnaar, 2010). For example, a sound source may be

²In discussing localization metrics, it is important to differentiate between the concepts of measure and metric. Both terms have several dictionary definitions and there is a certain degree of overlap between their meanings. In general, a measure is an objective amount of an attribute that is quantified against a certain standard. It is the extent or degree of something (e.g., a measure of distance or measure of central tendency) or a unit of measurement (e.g., a kilometer or standard deviation). A metric is a measure applied to a specific task. It is the degree to which a particular subject possesses the quality that is being measured. For example, a kilometer is a measure of distance. However, when the kilometer is used to determine how far a car can travel on a single tank of gas, it becomes a metric. In the context of this report, standard deviation is a general measure, but standard deviation used to quantify the localization error is a metric of this error.

³An imaginary (phantom) sound source is the perceptual image of a real sound source that does not coincide spatially with its true location.

perceived as located in-the-head during listening to a single sound source or several sound sources set at equal distances from the listener in an anechoic chamber (Toole, 1970). Similarly, in-the-head location of a phantom sound source may take place when each ear is stimulated by a separately generated sound (Plenge, 1974). The in-the-head sound source may appear to occupy the whole head or it may be perceived as a more discrete object located somewhere along an imaginary internal arc connecting the left and right ear. If the in-the-head sound source is perceived as being located closer to one of the ears of the listener, it is said to be lateralized toward this ear. Consequently, the terms lateralization and localization are used in psychoacoustic literature to describe judgments of the in-the-head and out-of-the-head location of a perceived sound source (Emanuel and Letowski, 2009; Howard and Rogers, 2012; Yost and Hafter, 1987). These terms are used regardless of whether the real sound source is located outside of the head or the sound is provided by earphones or a bone conduction system.

1.2 Auditory Distance Estimation

Auditory distance estimation is the judgment of the distance from the listener to the sound source. This judgment may take the form of a simple discrimination judgment (closer-farther), a sequential ratio judgment (half as far, twice as far), or an absolute judgment in some unit of distance. In order for this judgment to have real auditory meaning, the sound source has to be invisible. In the case of two sound sources concurrently emitting the sound and located at different distances from the listener, the listener may estimate the relative difference in distance between the two sources using the same types of judgments. Such relative judgments are referred to as *auditory distance difference* or *auditory depth* judgments. A good summary of the basic issues related to auditory distance perception can be found in Grantham (1995).

1.3 Spaciousness Perception

The third element of auditory spatial awareness, spaciousness, is the perception of being surrounded by sound and is related to the type and size of the surrounding space. It depends not only on the type and volume of the space but also on the number, type, and locations of the sound sources in the space. Unlike horizontal and vertical localization and distance estimation judgments, which are made along a single continuum, spaciousness is a multidimensional phenomenon that does not yet have a set of well-established dimensions and is usually described in relative terms or using categorical judgments. Issues related to auditory spaciousness are covered in books on concert hall acoustics, music, and audio recording technologies (e.g., Rasch and Plomp, 1999).

1.4 Goals, Format, and Structure of this Report

This report is intended to provide a common terminological and methodological platform for information exchange between laboratories investigating auditory localization and summarize the state-of-the-art knowledge about localization metrics and human localization ability. It is structured so as to first describe the general concepts related to spatial auditory awareness and

sensory mapping of the acoustic environment and then to use them as a backdrop for a more detailed discussion of the issues related to the planning, execution, and analysis of auditory localization studies

The initial part of the report (sections 2–4) is concerned with the formal and physiological bases of auditory localization. Section 2 starts with a discussion of various localization cues and their contributions to the general localization ability of a listener and is followed by a review of the effects of age, gender, and hearing loss on localization performance. Section 3 is an overview of the neurophysiology of spatial localization. Although this section is not directly related to the main purpose of the report, it is important for understanding ear pathologies mentioned in section 12 and outlines the processing of spatial information by the nervous system leading to the build-up of auditory spatial awareness.

The diversity of terms and points of reference used in auditory localization publications together with inconsistent semantics has been the source of some confusion in data interpretation. Therefore, section 4 presents the basic terminology used in spatial research with an emphasis on the various systems of coordinates used to describe the data. Further, in order to meaningfully interpret the character of overall localization error, it is important to determine both the constant error (accuracy) and random error (precision) components of localization judgments. Overall error metrics like root mean squared error and mean unsigned error represent a specific combination of these two error components and do not on their own provide an adequate characterization of localization error. Overall localization error can be used to characterize a given set of results but does not give any insight into the underlying causes of the error. All these issues are discussed in section 5, which includes a discussion of some elements of measurement theory and error metrology.

The main part of the report (sections 6–7) is devoted to the introduction of various localization metrics and circular data analysis. Common linear metrics used to describe directional data, along with some more advanced metrics, are explained and compared, and their advantages and limitations outlined. However, the fundamental property of localization data is that they are by their nature angular and thus constitute circular (spherical) variables. Such data, in general, cannot be described by a linear distribution as assumed in classical statistics. The azimuth and elevation of sound source locations define an ambiguous conceptual sphere, which can only be fully analyzed with the methods of spherical statistics. The appropriate methods of statistical analysis for such two-dimensional (2-D) (circular) and 3-D (spherical) data are, respectively, the tools of spherical and circular statistics. However, if a set of directional judgments is relatively concentrated around a central direction, the differences between the circular and linear metrics may be minimal, and linear statistics may effectively be used in lieu of circular statistics. The conditions under which the linear analysis of directional data is justified are outlined in section 7 on circular data analysis.

The subsequent part of the report (sections 8–12) provides a discussion of the various types of localization tasks, localization reversal errors, and attempts to use auditory localization tasks in clinical audiology. The discussion is supported by results of various research studies in order to provide the reader with state-of-the-art reference data. Although the focus of the discussions conducted in sections 8–12 is on auditory localization in the sound field with unoccluded ears, some data for the earphone-based *auditory virtual reality* (AVR) environments are also provided. However, the accuracy of specific spatial renderings implemented in various AVR studies may vary and affect localization data (e.g., Bronkhorst, 1995; Martin et al., 2001; Wightman and Kistler, 1989b). There are also important differences in the stimuli used in such studies that may affect localization error. Therefore, the data reported in such studies need to be treated with caution.

The final part of the report includes a review of complex localization scenarios involving multiple and moving sound sources (sections 13–14), a short summary (section 15), and two methodological appendices focused on the effects of directional response (appendix A) and listener learning/practice (appendix B) on the results of localization studies. The preferred type of directional response and listener learning/practice effects are the two most debated elements of localization study methodology. Therefore, these two appendices are intended to provide background information on both issues for readers designing their own localization studies. An extensive list of references mentioned in the report is provided in section 16.

2. Basis of Auditory Localization

The human auditory localization ability depends on a number of anatomical and physiological properties of the auditory system as well as on a number of behavioral factors. These properties and behaviors are referred to in the literature as *localization cues*. These cues are generally classified as binaural, monaural, dynamic, and vision and memory cues. The most important of these cues are the binaural cues that are related to the presence of two external ears located on opposite sides of the head⁴ and serving as the entry points to the auditory system. This configuration causes a sound coming at the listener from an angle to have a different sound intensity and time of arrival at each ear. Moreover, individual anatomic differences in the size and shape of both the head and external ears of the listener affect the perceived direction of incoming sound by creating a characteristic pattern of the diectional properties of the human head (HRTF, see section 2.2) that uniquely modifies the spectrum of incoming sound for each person (Watanabe et al., 2007). In addition to the above anatomical cues and the slight natural asymmetry of ear placement on the head (King, 1999; Knudsen, 1984), the listener's movements, familiarity with the sound source, visibility of a potential sound source, and expectations may

⁴Typically, the human ears are not located at either end of a diameter of the head but are set back by about 10° from the coronal plane (Blauert, 1974/2001).

affect the perceived direction of an incoming sound (e.g., Haas, 1951; Jongkees and Groen, 1946; Wallach et al., 1949).

2.1 Binaural Cues

2.1.1 History

The first widely known study in auditory localization was carried out by Venturi (1796) who walked around a listener playing a note on a flute at intervals and demonstrated that people could point to the direction from which the sound of the flute was coming. He attributed this capability to sound intensity differences at each of the two ears of the listener. However, despite being published in three languages, his work did not generate much interest among his contemporaries. Very little research was done in the area of auditory localization until the last quarter of the 19th century, when several authors experimentally confirmed the importance of sound intensity differences between the ears for sound source localization (Steinhauser, 1879; Strutt [Lord Rayleigh], 1876; Thompson, 1877; 1881). This difference is caused by the acoustic shadow and baffle effects of the head and results in a lower sound intensity at the ear located farther away from the sound source. However, the difference is practically negligible for low frequency sounds below 200 Hz, and the fact that these sounds can still be localized baffled initial researchers studying auditory localization.

Thompson (1878) seems to have been the first to suggest that low frequency sound sources can be localized on the basis of sound phase differences between the ears. However, his suggestion was rejected by his contemporaries due to the then (1863) popular theory that people are “phase deaf.” It was not until 1907, when Lord Rayleigh experimentally showed that the direction toward a low frequency sound source could be determined on the basis of the phase difference between the sounds arriving at the two ears that the phase difference mechanism of sound localization was generally accepted (Strutt [Lord Rayleigh], 1907). This difference is caused by the different distances the sound has to travel to each of the ears and, in the case of periodic sounds, can be expressed as phase difference.

Phase difference can also be expressed as time difference. Time difference has a more general meaning because it can also be applied to impulse and other non-periodic signals. The first suggestion that the position of a sound source can be localized on the basis of the difference in the time of arrival of the sound wave to the two ears was made by Mallock (1908) and shortly later corroborated by Aggazzotti (1911), Hornbostel and Wertheimer (1920), and Klemm (1920). The above phase/time localization mechanism has been shown to work well at low frequencies, but for sounds at frequencies exceeding about 1.2 kHz (Middlebrooks and Green, 1991), the wavelengths become shorter than the distance between the ears of the listener and phase differences become an ambiguous cue (Hartley, 1919; More and Fry, 1907; Strutt [Lord Rayleigh], 1907; Wilson and Myers, 1908). This observation prompted Strutt to propose the *duplex theory of localization*, in which phase differences and intensity differences are two complementary localization mechanisms allowing humans to localize low and high frequency

sound sources, respectively (Strutt [Lord Rayleigh], 1907). This theory was later developed by his followers (Stevens and Newman, 1936). It is important to stress that although directional perception has been accepted as a 3-D phenomenon since the time of Venturi, most of the early research and subsequent theories of auditory localization have exclusively focused on localization in the horizontal plane.

2.1.2 Duplex Theory

The two auditory mechanisms comprising the *duplex theory of localization* are commonly referred to in the modern literature as the *interaural intensity difference* (IID) and the *interaural time difference* (ITD) mechanisms. In the case of continuous pure tones and harmonic complexes, the term *interaural phase difference* (IPD) is used in place of ITD since such sounds have no clear reference point in time. The IID and ITD (IPD) together are called the *binaural*⁵ *localization cues*. As discussed, the IID is the dominant localization cue for high frequency sounds, while the ITD (IPD) is the dominant cue for low frequency sounds (waveform phase difference). However, it was later discovered that the ITD (IPD) is also an important cue in the localization of high frequency sounds whose temporal envelopes have different onsets at the left and right ear (Henning, 1974; 1980; McFadden and Pasanen, 1976; Zhang and Wright, 2007). The resulting localization cue is frequently referred to as the *interaural envelope difference* (IED). In a similar fashion, the IID cues have been found to be important for the localization of low frequency sounds in the case of near-field sound sources (Brungart and Rabinowitz, 1999; Brungart et al., 1999; Shinn-Cunningham et al., 2000). See section 2.1.5 for more information on the differences in the localization of far- and near-field sound sources.

The transition zone between low and high frequency binaural mechanisms extends approximately from 800 to 1600 Hz. In this region localization performance is the poorest (Stevens and Newman, 1936; Sandel et al., 1955). As regards the low and high frequency regions, Langford (1994) reported that people who discriminate the low frequency ITD cues well also discriminate the high frequency IIL cues well, although individual differences are large. The mechanisms of both binaural cues (IID and ITD) are shown in figure 1.

⁵The term binaural was most likely first used by Alison (1861) who used this term to describe his differential stethophone and later by Thompson (1878) to describe two-ear phenomena.

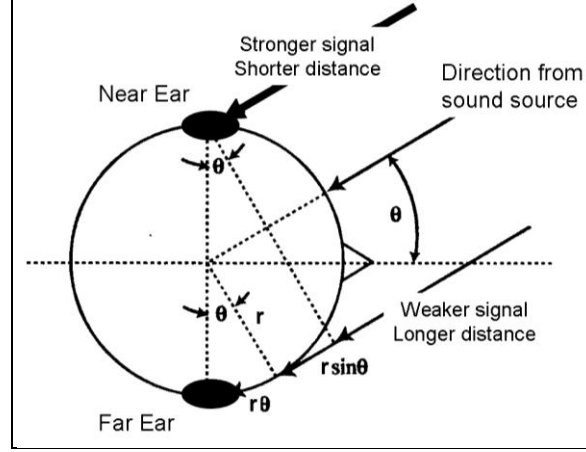


Figure 1. Binaural localization cues caused by the differences in sound intensity (stronger signal and weaker signal) and sound time of arrival (near and far ear). Adapted from Shaw (1974).

2.1.3 Interaural Time Difference (ITD)

The time difference (ITD) is the dominant binaural cue for humans since it is a major cue for low frequency sound source localization as well as an important secondary cue for high frequency sound source localization (Macpherson and Middlebrooks, 2002). The ITD resulting from a plane sound wave arriving at the near and far ear of the listener can be approximately calculated on the basis of a frequency-independent model of a wave traveling around a sphere as (Woodworth and Schlosberg, 1954)

$$ITD = \frac{r}{c} (\theta + \sin \theta), \quad (1)$$

where r is the approximate radius of the listener's head, θ is the angle between the listener's medial axis and the direction toward the sound source (see figure 1), and c is speed of sound. For angles $\theta < 45^\circ$, $\theta \approx \sin \theta$ (underestimation error less than 5%) and equation 1 can be rewritten as

$$ITD = \frac{2r}{c} \sin \theta. \quad (2)$$

However, the above frequency-independent model of a wave traveling around a sphere is only a good model of ITD at high frequencies (above 3000 Hz), whereas at low frequencies the diffraction of sound waves around the human head causes longer ITD. In general, the ITD can be calculated from the following formula (Kuhn, 1977)

$$ITD = \frac{ar}{c} \sin \theta, \quad (3)$$

where $a=3$ for frequencies below about 500 Hz ($\theta < 90^\circ$) and gradually decreases with frequency to $a=2$ for frequencies above 2000 Hz ($\theta < 60^\circ$)⁶. In addition, ITD decreases slightly with temperature since the speed of sound $c = 331 + 0.6T$, where T is the ambient temperature in $^\circ\text{C}$. For example, for $f < 500$ Hz, $\theta = 90^\circ$, $r = 9.0$ cm (Bushby et al., 1992), and $T = 15$ $^\circ\text{C}$, the ITD is 794 μs . This is the greatest possible ITD, also called the critical ITD, for a listener with a head radius of 9 cm listening under the stated conditions. The critical ITD value and the angular range in which ITD can be used as a localization cue increase with increasing head size but decrease with increasing frequency and temperature. Heffner (2004) argued that the larger the head size the more robust the binaural cues are, since in addition to increasing the critical ITD value and the angular range, a larger head creates a greater acoustic shadow, which in turn allows for larger IIDs.

In the context of low frequency sound localization, it should be noted that Savel (2009) studied the horizontal localization ability of 50 adult listeners using low-frequency bands of noise and observed a frequent left-hemisphere advantage in localization accuracy and precision (see section 5) for right-handed (vs. left-handed) and male (vs. female) listeners. She inferred that this asymmetry may be related to differences in brain organization and temporal processing between the respective groups.

2.1.4 Interaural Intensity Difference (IID)

It is generally assumed that the diffraction effect of an average human head becomes negligible below 1 kHz and that at frequencies below 1.5 kHz, the IID is too small to facilitate sound localization. In contrast, the IID reaches 10–35 dB for high frequency sounds (e.g., 10 dB at 3 kHz and 35 dB at 10 kHz) depending on the lateral position of the sound source and the sound frequency (Feddersen et al., 1957; Kuhn, 1977; 1987; Mills, 1958; Middlebrooks and Green, 1991; Middlebrooks et al., 1989). Also, the IID effect across the middle and high frequency region has a net effect of an 8 dB improvement in signal-to-noise ratio when the target sound source and the masking sound source are located at opposite sides of the head (e.g., Bronkhorst, 2000). The general relationship between the maximum ITD and IID and sound frequency is shown in figure 2.

⁶The decrease in the value of a is nearly monotonic except for a small drop to about $a=1.7$ over the 1400–1600 Hz frequency range. This minimum a value (and the corresponding ITD value) occurs precisely over the same frequency range as where listeners exhibit the poorest localization discrimination (Mills, 1958).

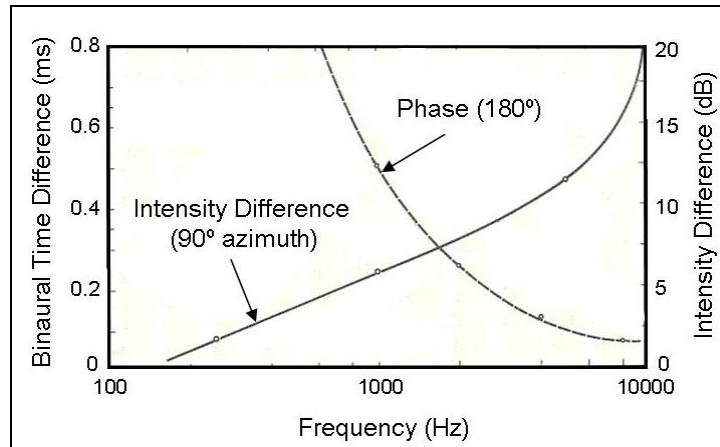


Figure 2. General dependence of ITD (dashed line, left scale) and IID (solid line, right scale) on frequency. Adapted from Gulick et al. (1989).

The general monotonic relationship between the IID and the azimuth angle is only the first approximation of the actual relationship. Due to the physics of wave diffraction around the head (Kuhn, 1977; 1987), the maximum IID appears not at 90° but at a smaller angle, making the relationship between the IID and azimuth angle non-monotonic. However, the higher the frequency, the higher the IID and the larger the angle at which the IID reaches its maximum (Macaulay et al., 2010). Thus as frequency increases, the angle of maximum IID approaches 90° and the non-monotonicity is gradually reduced. The non-monotonic behavior of the IID does cause large localization uncertainty for mid-high frequency tones (1000–1600 Hz) that arrive from locations more than 30–40° off the midline (Firestone, 1930; Macaulay et al., 2010; Mills, 1958; Nordlund, 1962ab).

2.1.5 Far-field and Near-field

In an open field and for a sound source far away from the listener's head, both ITDs and IIDs are independent of the distance between the sound source and the listener. However, as the distance between the sound source and the listener decreases, the difference between the sound intensities reaching the listener's left and right ear increases, the acoustic shadow behind the listener's head grows larger, and the curvature of the sound field increases⁷ (Brungart and Rabinowitz, 1996). These effects cause the IID to gradually increase and become dependent on the distance between the listener and the sound source.

The region in which IIDs are independent of the distance between the sound source and the listener is referred to in the localization literature as the *far field*, and the region in which they are distance-dependent is called the *near field* of the head. The near field is generally assumed to extend up to five times the radius of the head (or about 0.5–1.0 m) away from the center of the

⁷The increase in the curvature of the sound field is due to the fact that at short distances from the sound source, the plane wave approximation of the wave front is no longer valid.

listener's head (Brungart, 1999; Duda and Martens, 1998), depending on the size of the head. The relation between distance and IID in the near field is dependent of both the azimuth angle and sound source frequency (spectrum). For example, for a sound source emitting a 500-Hz tone and located at a 90° angle to the listener, the far-field IID at 1 m distance is about 3 dB and the near-field IID at 20 cm is as large as 13 dB (Brungart and Rabinowitz, 1996). Therefore, as a result of the increased IID in the near field, the perceived location of the sound source is being shifted laterally.

Similarly, the changes in the IID with the changes in the distance between the listener and the sound source affect the listener's judgment of the actual distance to the sound source making it actually more accurate than in far field, especially for sound sources located at the lateral directions (Brungart, 1998). In contrast, to the IID changes, the ITD remains relatively independent of distance in the near field and its small changes do not affect distance perception (Brungart, 1998; Duda and Martens, 1998). Brungart (1998) measured the compound localization error (see section 5) in the 3-D space in proximity of the listener's head and reported an average error of 16.5°. This error is similar in size to the average far field compound localization error (21.1°) reported by Wightman and Kistler (1989a) indicating similar localization accuracy in both far field and near field. However, the number of reversal errors⁸ reported by Brungart (1998) was noticeably larger (16.4%) than reported in far field studies (2%–11%).

2.1.6 Limitations of Binaural Cues

Many experimental studies have confirmed that binaural cues are the main localization mechanisms in the horizontal plane. The ITD provides left-right localization cues at low frequencies, below ~800 Hz, and the IID provides left-right localization cues at high frequencies, above ~1600 Hz. In the 800–1600 Hz range neither individual binaural cue is particularly effective, but working in tandem they provide somewhat more effective than each of them individually localization capability.

If one assumes that both the ITD and IID cues are equally effective across their optimum frequency ranges, then the low- and high-frequency parts of a given sound spectrum should be equally localizable. A frequency that divides the sound spectrum into two parts that are “equal” with respect to some specific criterion (such as localizability) is sometimes referred to as the center of gravity of the sound spectrum. In the case of localizability, the crossover frequency for ITD and IID cues, say 1200 Hz, does not exhibit this center of gravity property, that is, the part of a sound below 1200 Hz is not localized just as well as the part above 1200 Hz. King and Oldfield (1997) reported that for the three subjects they tested, the center of gravity was in the 8–9 kHz range. This supports the general observation that high frequency sounds are localized

⁸Reversal errors are discussed in section 10.

more effectively than low frequency sounds and that the localization effectiveness of IID cues is superior to that of ITD cues.

Despite their great role in horizontal localization the binaural cues are only marginally useful for vertical localization or front-back differentiation. This is due to the spatial ambiguity caused by left-right head symmetry commonly referred to as the *cone of confusion* (Wallach, 1939). The cone of confusion is the imaginary cone extending outward from each ear along the interaural axis and representing sound source locations producing the same interaural differences. The concept of cone of confusion is shown in figure 3.

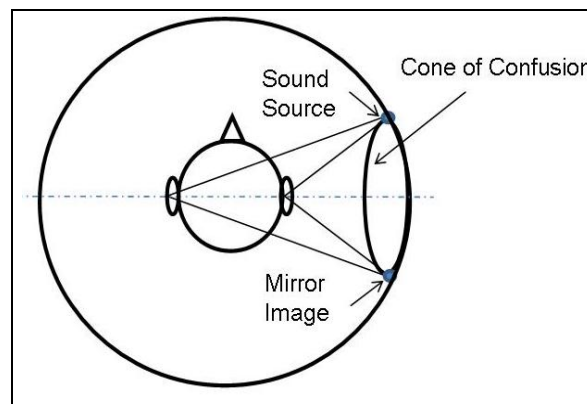


Figure 3. The concept of the cone of confusion.

In general, sound source locations on the surface of the cone of confusion cannot be identified using binaural cues, although asymmetry in ear placement on the head and in the shape of the pinnae provides some disambiguation. Nonetheless, in order to reliably differentiate between specific positions on the surface of the cone of confusion, other cues are needed. These cues are called monaural cues as they do not depend on the presence of two ears.

2.2 Monaural Cues

Monaural cues result from sound energy absorption by the head, shadowing and baffle effects of the outer ear (pinna)⁹, and sound reflections caused by the outer ear, head, and shoulders (Batteau, 1967; Bloch, 1893; Gardner and Gardner, 1973; Lopez-Poveda and Meddis, 1996; Mach, 1906/1959; Musicant and Butler, 1984; Steinhauser, 1879). Even the presence (or lack) of hair and hair arrangement may affect monaural cues (Treeby et al., 2007). All these physical effects result in spectral changes in the sounds arriving at the ears and are, therefore, often referred to as *monaural spectral cues*. Acoustic shadowing occurs when a sound wave is reflected by an encountered object, causing an acoustic shadow behind the object. In the case of the human head, this is particularly noticeable for frequencies above 1 kHz (e.g., Mills 1972). The baffle effect is an increase in sound pressure in front of an object due to the reflected energy.

⁹Bloch (1893) seems to be the first one to demonstrate that changes in the shape of the pinna results in changes in the perceived locations of sound sources.

Both of these effects and the specific reflections from the different parts of the pinna, head, and torso produce peaks and troughs in the sound spectrum that are unique for each sound source location in space¹⁰ relative to the position of the listener (Bloom, 1977; Butler and Belendiuk, 1977; Watkins, 1978). Reflections from the torso (shoulders) affect sounds in the frequency range of 2–3 kHz (e.g., Algazi et al., 2001; Gardner, 1973), while pinna effects are most pronounced above 3–4 kHz (e.g., Roffler and Butler, 1968b). This means that monaural cues generated by pinnae and body reflections are high frequency needed for accurate sound source localization (e.g., Butler, 1975). The absence of pinna cues (e.g., by filling the concaves of the pinna) greatly decreases localization accuracy (Gardner and Gardner, 1973; Oldfield and Parker, 1984b; 1986; Roffler and Butler, 1968b) and destroys the “outside-of-the-head” spatial impression (Plenge, 1974). Physical differences between the left and right pinnae and the overall left-right asymmetry of the human body also generate interaural spectrum differences (ISDs), which additionally differentiate the sounds entering each ear. Further, the lateral part of the human ear canal is slanted about 15° upwards while the medial part of the canal is slanted downwards, providing potentially additional mechanism for differentiating sounds coming from above and from below (Shaw, 1996). These differences create additional spectral cues that are related to the monaural cues and aid localization in the horizontal plane (Searle et al., 1975; Shaw, 1974; 1982).

A number of studies demonstrated that people listening with just one ear can localize sound sources in the horizontal plane although such localization accuracy is much poorer than with two ears and all localization judgments are shifted toward the active ear (Belendiuk and Butler, 1975; Butler 1987; Butler and Flannery, 1980; Butler and Naunton, 1967; Jin et al., 2004; Morimoto, 2001; Oldfield and Parker, 1984a; 1986; Van Wanrooij and Van Opstal, 2004). Such localization ability is proof that horizontal localization can, to some degree, be facilitated by monaural cues. In this case, the emitted sound must contain energy above ~5 kHz, that is, in the frequency range where the pinna cues have an appreciable role. Batteau (1967) and Fisher and Freedman (1968) seem to attribute the monaural localization ability to a sequence of time-delayed reflections from the pinnae surfaces. However, it is unclear to what extent this mechanism is helpful when binaural cues are present. Macpherson and Middlebrooks (2000, p. 2233) asserted that in this situation “monaural spectral cues had little or no influence on perceived lateral angle.”

Monaural spectral cues and the related interaural spectral cues help the binaural cues resolve sound source laterality, but they are most critical for vertical localization and front-back differentiation (e.g., Blauert 1974/2001; Gardner and Gardner, 1973; Oldfield and Parker, 1984b). The relative importance of the interaural spectral cues to the localization of sound sources at different elevations is hard to generalize since it varies with the lateral position of the sound source (e.g., Jin et al., 2004). Oldfield and Parker (1986) demonstrated that monaural localization in the vertical plane, which does not take advantage of the interaural spectral cues, is

¹⁰The differences in monaural cues are much greater in vertical plane than in horizontal plane where they are much weaker than the corresponding differences in the binaural cues.

relatively good but somewhat less accurate than binaural localization. Similar data were reported by Humanski and Butler (1988) and Slattery and Middlebrooks (1994). However, the results of such monaural studies are hard to interpret since “monaural listening actually provides conflicting and unnatural cues to sound source position [and] one cannot be certain that the listener’s judgments of apparent sound source position will reflect only the influence of spectral cues” (Wightman and Kistler, 1997, p. 1061).

The spectral cues that are the most important for accurate front-back and up-down differentiation are located in the 4–16 and 6–12 kHz frequency range, respectively (e.g., Langendijk and Bronkhorst, 2002a). Hebrank and colleagues (Hebrank and Wright, 1974; Wright et al., 1974) identified the major monaural cues in the median plane as notch (N1) between 4 and 8 kHz (front cue), peak (P1) between 7 and 9 kHz (overhead cue), and peak (P2) between 10 and 12 kHz (back cue) in the sound spectrum. Langendijk and Bronkhorst (2002b) confirmed that these two peaks and the notch are sufficient to obtain realistic virtual sounds in a 3-D space. The overall envelopes of the sound spectra recorded in the ear canal are relatively similar across people, but the major peaks and notches have a tendency to be shifted down for people of larger size (Middlebrooks et al., 1989). Asano et al. (1990), Butler and Humanski (1992), and Algazi et al. (2001)—but not Morimoto et al. (2003)—reported that in addition to high frequency monaural cues, the low frequency (<2 kHz) cues may also be important for front-back differentiation and vertical localization, especially for elevations exceeding 45°, where the monaural high frequency cues become less effective. This effect may be due to the asymmetrical locations of pinnae on the head surface and to elevation-dependent low-frequency sound modifications caused by head diffraction and torso reflections (e.g., Gardner, 1973; Genuit and Platte, 1981; Kuhn, 1987). These modifications are small for sound sources located in the median plane, but they gradually become more pronounced at larger azimuth angles, that is, at angles away from the median plane (e.g., Algazi et al., 2001). This dependence may explain the poor localization of low frequency sound sources located in the median plane reported by Morimoto et al., (2003).

Both the binaural and monaural cues are unique properties of each individual person due to the unique anatomic features of each person’s head. These anatomical differences are reflected in the pattern of the *head related transfer functions* (HRTFs) of each person’s head. An HRTF is a frequency-dependent transfer function between sound source location in space and the point at the entrance to the listener’s ear canal. A pair of such functions, for the left and right ear, uniquely represents the location of a sound source in the space as heard by a given listener (Watanabe et al. 2007). These functions are, in general, not transferable between individuals and are most different for frequencies in the high frequency region of 5–10 kHz, where the pinna contributions are the largest. The maxima and notches in the HRTF pattern can be as large as 25 dB (e.g., Mills, 1972; Wightman and Kistler, 1989a), and their size and distribution depend on the monaural cues and the slight natural asymmetry in ear placement on the head (e.g., King, 1999; Knudsen, 1984).

The differences in individual HRTFs create the cues that each person learns during their lifetime. This is the reason why people who do not seem to differ in localizing real-world sounds may differ quite dramatically when exposed to the same AVR environment preprocessed through somebody else's HRTF. Wenzel et al. (1993) demonstrated that the rate of localization error for an AVR in which individually measured HRTFs (individualized HRTFs) are used is much lower than for an AVR based on a non-individualized HRTF (i.e., an average HRTF or HRTF from a representative listener). However, it should be noted that not all the details of an individual HRTF need to be captured exactly in order to preserve the natural locations of sound sources. Kulkarni and Colburn (1998) studied the effect of spectral smoothing of HRTFs and demonstrated that "crude approximations of the natural ear-input signals were perceived as natural provided that these waveform were made to change in a manner consistent with the movement of the listener head" (p. 748). Pulkki (2001) hypothesized that good localization in virtual space is dependent on the preservation of the pattern of pinna-mode frequencies rather than the specific details of peaks and notches. This means that if the specific frequencies of spectral peaks and notches are preserved, the relative sizes of the peaks and notches are not critical.

2.3 Dynamic Cues

2.3.1 Head Movements

In addition to binaural and monaural cues, spatial localization ability in both the horizontal and vertical planes is also dependent on head movements, which cause momentary changes in the peak-and-trough pattern of the sound spectrum at each ear (e.g., Fisher and Freedman, 1968; Iwaya et al., 2003; Jongkees and Veer, 1958; Lambert, 1974; Ohtsubo et al., 1980; Perrett and Noble, 1997a; Thurlow and Runge, 1967; Thurlow et al., 1967; Wallach, 1940; Young, 1931). These dynamic cues are the most important for low frequency sounds below 2 kHz (Thurlow and Mergener, 1970). Most authors report much larger localization errors when the listener's head is fixed than when the listener is allowed to turn his head toward the source of sound (e.g., Link and Lehnhardt, 1966) and several authors consider head movements as the most essential mechanism in solving front-back uncertainty (originally proposed as such by Van Soest, 1929, and later corroborated by Börger et al., 1977; DiCarlo and Brown, 1960; Mackensen, 2003; Majdak et al., 2010; Nordlund, 1962ab; Wallach, 1939; and Wightman and Kistler, 1999). Thurlow et al. (1967) studied the localization performance of listeners who were allowed to move their heads while keeping their torso straight. They observed that the listeners usually moved their head back and forth more than once and that most head movements were small horizontal rotations. If the sound is long enough (600–800 ms), such movements of the head allow the listener to disambiguate front-back confusions and focus on the direction of the incoming sound (e.g., Iwaya et al., 2003; Lambert, 1974; Noble, 1987; Perrett and Noble, 1997a; Rakerd and Hartmann, 1986; Thurlow and Runge, 1967). For the same reason, a train of repeated pulses results in better auditory localization of the sound source than a single pulse (Macpherson and Middlebrooks, 2000). In general, the effects of pinna cues and head

movements seem to be additive for sound source localization in the horizontal plane. The absence of one or the other results in a similar loss of localization acuity and a similar change in error pattern (Muller and Bovet, 1999). However, it needs to be added that head movements may also result in localization errors. Such negative effects of head movements may be observed if a short sound stimulus is heard during a rapid head movement (e.g., Cooper et al., 2008).

Wallach (1939, 1940) hypothesized that small head movements in the horizontal plane should also help resolve the sound source position in the vertical plane. Wallach argued that the horizontal rotation of the head should eliminate front-back errors by changing and contrasting the interaural differences (especially ITDs) caused by sound sources located in the front or rear. For a given range of head rotations, these changes would be the greatest for horizontal locations, nonexistent for vertical locations ($\pm 90^\circ$), and intermediate for partially elevated sound source locations. Therefore, these rotations should also allow some degree of discrimination of the sound source's vertical displacement. The resulting cue, referred to as *Wallach cue*, depends on the presence of low frequency (below 2 kHz) energy in the signal and is most effective for sound sources located in the upper front of the median plane (Perrett and Noble, 1997a). The *Wallach cue* seems to serve as a secondary cue for vertical localization, and if the monaural pinna cues are sufficiently strong, its presence does not noticeably improve vertical localization performance (although it is still important for resolving front-back uncertainty).

Other head or body movements that affect localization performance are tipping the chin toward the chest, tilting the body, or pivoting the head toward one or the other shoulder. While such movements may help to determine the degree of elevation of the sound source (Perrett and Noble, 1997a), they progressively displace the apparent midline in the direction opposite to the direction of the movement and affect both localization performance in the horizontal plane and localization of the sound source located just above the listener's head (e.g., Comalli and Altshuler, 1971; Teubert and Liebert, 1956). Therefore, it is very important that listeners participating in localization studies are always reminded to keep their head straight, even if small rotational movements are permitted.

While modern studies mostly employ very short sounds, sounds as long as 3–4 s were used in older studies, and the effects of head movements were easier to observe (e.g., Angell, 1903; Thurlow and Mergener, 1970). It seems that a minimum duration of 600–800 ms is needed to accommodate the effects of head movements. For example, Noble (1990) observed that head movements had minimal effect on the localization of a 500-ms sound but caused a considerable improvement in localization performance when the sound duration increased to 1.5 s. Similar data were reported by Thurlow and Mergener (1970).

Regardless of the presence or lack of head movements, the sound event may need to be of a certain duration to allow the listener to build a spatial image of the location of the sound source (e.g., Blauert, 1974/2001; Burger, 1958; Kietz, 1953). For example, Pollack and Rose (1967) observed that with no head movements, changing the signal duration from 3 ms to 1 s reduced

the average localization error from 10° to 2° . Tobias and Zerlin (1957; 1959) studied the effect of stimulus duration on lateralization threshold, which is the smallest noticeable change in sound source lateralization within the head, using noise bursts with durations from 10 ms to 1.9 s. They concluded that for sound duration up to 700 ms, the threshold varied systematically with the stimulus duration and became duration independent above 700 ms. These reports indicate that sound duration affects localization performance beyond just allowing head movements. It is noteworthy that the duration above which head movements meaningfully contribute to front-back disambiguation also coincides with the perceptual boundary between short and long sounds in the perception of music (450–900 ms [Clarke, 1999; Fraisse, 1978])). A longer duration also permits the listener to recognize familiar sounds (see section 2.5). In one notable study, Noble and Gates (1985) allowed the listeners to move their head and body (while remaining seated) and control the duration of the presented stimuli. They reported far better localization accuracy than was earlier reported by Roffler and Butler (1968b), who used similar signals but restricted the listener's movements.

2.3.2 Sound Onset and Precedence Effect

Another kind of dynamic cue, this time related to the signal as opposed to the listener, is the temporal envelope of the auditory signal. An important property of the auditory system is that it primarily reacts to the onset of a sound event (and to some degree its offset) while suppressing the effects of the steady-state part of the sound (Stecker and Hafter, 2002). Both the sound identification and sound source localization abilities of the listener depend greatly on the form and duration of the sound onset, especially in enclosed spaces (e.g., Elfner and Tomsic, 1968; Rakerd and Hartmann, 1986). According to Wilska (1938; table 5) tones in the frequency range of 400–6400 Hz with on- and off-set durations ≤ 1 ms can be localized with less than 3° error across the whole frequency range, while 100 ms on- and off-set durations lead to localization errors ranging from 5° to 15° with increasing tone frequency.

The importance of the front-end of the arriving waveform for sound source localization has been termed the *precedence effect* (Wallach et al., 1949; Litovsky et al., 1999), *Haas effect* (Haas, 1951), or *the law of the first wavefront* (Cremer, 1948). Historical background of this effect going back to works of Henry (1851; 1856), Fay (1936), and Hall (1936) can be found in Gardner (1968). According to this law, the listeners make localization judgments based on the earliest arriving sound, ignoring any other similar sounds arriving from other directions (e.g., reflections of the primary sound from the walls in a closed space). If the secondary sound is delayed by 1 to 20 ms and has an intensity not exceeding the intensity of the primary sound by more than 10 dB, only one sound is heard, and that sound is the primary sound¹¹. If the secondary sound is delayed by less than 1 ms, it is perceptually integrated with the primary sound, and the integrated sound is heard as arriving from a direction that is the average of both

¹¹The precedence effect is a binaural effect and exists only in a real sound field. Green (1976) demonstrated that while a 6-ms time delay between two identical pulses cannot be heard in a room, it can easily be heard with one ear over an earphone.

directions (Hartmann, 1997; Shinn-Cunningham et al., 1993). If the secondary sound arrives after a delay longer than 20 ms, it is heard as an echo. The precedence effect causes some counterintuitive spatial effects such as the Franssen Effect¹² (Franssen, 1960) and the Clifton Effect¹³ (Clifton 1987).

An audible sound onset and the existence of the precedence effect are the main reasons that we can localize sound sources even in reverberant environments with multiple reflective surfaces as long as we hear the beginning of the primary sound. This is also why acoustic sources generating impulse sounds (e.g., firearms) are easier to localize than sources emitting continuous or slowly rising long sounds. This effect of sound envelope supports the notion that *short impulses* (5–2000 ms) with onset time <5 ms are the easiest sounds to localize in closed spaces (e.g., Christian and Röser, 1957; Hartmann, 1983a; Laroche, 1994).

In closed spaces, reflected sounds add to the reverberant character of the perceived sound but are not heard separately. As Hartmann (1997) pointed out, if the reverberation is not too excessive, we frequently do not realize its presence until we hear a recording of the sound in a given space played in reverse. Localization acuity for a leading-lagging pair of sounds is almost as good as for a single sound source with a slight displacement toward the direction of the lagging stimulus (Zurek, 1980; Litovsky and Macmillan, 1994). However, it is important to stress that using the precedence effect and the ability to localize a single sound source are different phenomena. While normal infants can localize a single sound source soon after birth, they must learn to use the precedence effect, which generally occurs after 6 months of postnatal cortical development. Similarly, unilateral ablation of the auditory cortex in cats disrupts the precedence effect but does not affect the localization accuracy of a single sound source. See Hartmann (1997) and Zurek (1987) for more information.

2.4 Vision and Memory Cues

Other potential localization cues include visual cues (e.g., Lackner, 1973; Wallach, 1939), vestibular cues (discussed in section 7) (e.g., Meurman and Meurman, 1954; Wallach, 1939), prior knowledge of the stimulus (e.g., Angell and Fite, 1901ab; Kietz, 1953; Pierce, 1901; Rogers and Butler, 1992), and the listener's expectations. These cues are termed in this report as vision and memory cues.

¹²The Franssen Effect is an auditory localization illusion in which the listener incorrectly identifies the sound source emitting the sound. It can be demonstrated by placing two loudspeakers (1 and 2) in a room at a certain distance apart. At the beginning of the demonstration a pure tone abruptly begins to be emitted from loudspeaker 1. After some time the signal is gradually faded over from loudspeaker 1 to loudspeaker 2 keeping the total signal power constant. At the end of the fading phase, the pure tone is only emitted from loudspeaker 2, yet the listener still localizes loudspeaker 1 as its source. A good discussion of the Franssen Effect can be found elsewhere (Hartmann and Rakerd, 1989b).

¹³The Clifton Effect can be demonstrated by emitting a series of clicks from two loudspeakers, one loudspeaker emitting the primary (strong) clicks and the other emitting the secondary (weak) clicks with a 10-ms delay (three click pairs per second). An abrupt reversal of the directions from which the two clicks come from renders both sound sources temporarily audible, but after a few more repetitions the source of the lagging (weaker) clicks “disappears” again.

Many observations indicate that visual perception dominates auditory perception with respect to localization and that people have a tendency to trust their eyes more than their ears (Ghirardelli and Scharine, 2009; p. 605). This, to some extent, can be due to the fact that the auditory localization ability is less acute than the visual localization ability. This difference is more dominant in the vertical plane, where listeners consistently tend to underestimate the elevation of the sound source, than in the horizontal plane (Dobrev et al., 2005). Heffner and Heffner (1992) hypothesized that the relatively poor acuity of the auditory localization system in comparison to visual localization system may be due to the fact that its main role is to direct vision toward the sound source rather than to be a discriminative system on its own (Heffner and Heffner, 1992). This seems to be supported by the fact that the acuity of auditory localization among various species is inversely proportional to the width of the field of best vision (Heffner, 2004). See also section 4.

When a person sees a sound source, their auditory localization acuity artificially increases by pointing toward the visual object (Shelton and Searle, 1980; Stein et al., 1989; Godfroy and Roumes, 2004). Even more importantly, if a person sees an object that could be the source of an arriving sound, they may frequently select this object as the source regardless of whether this object actually produced the sound or not (Jackson, 1953; Warren, 1970). In general, if vision and hearing report conflicting information, vision almost always dominates hearing. This phenomenon has been termed the *capture effect* (e.g., Ghirardelli & Scharine, 2009). The most widely known form of the capture effect is the *ventriloquism effect* (VE) (Howard and Templeton, 1966) in which the listener perceives the ventriloquist's speech as coming from ventriloquist's dummy. The visual capture effect is very strong when the angular difference in position between the visual object and the sound source is less than 30°, although Thurlow and Jack (1973a) reported some listeners had confusion for angles as large as 60°. The closer the visual target is to the midline, the more likely the capture effect (Hairston et al., 2003).

In contrast to the effects caused by the visible sound sources, it is not entirely clear whether simply the presence of a visual environment influences the accuracy of localization of invisible (or indiscernible) sound sources in space. Shelton et al. (1982) reported that listeners who could move their head and see their surroundings made fewer localization errors than listeners who had their eyes covered with opaque goggles, even when no visual information was associated with the sound sources. They further hypothesized that head movements improve localization acuity only in the presence of visual cues. In contrast, Bauer and Blackmor (1965) observed that auditory localization acuity was the same in daylight and in darkness. Lovelace and Anderson (1993) compared listeners' localization acuity of non-visible sound source with eyes open and closed during sound presentation and also found no difference. They also argued (p. 843) that if any effect of vision on auditory localization acuity should be expected it should be a negative rather than positive effect "since visual influence can introduce interference that would increase the magnitude of error in sound localization (as occurs in visual capture) one might even hypothesize that closing one's eyes might result in improved accuracy of sound localization."

This view is supported by extensive anecdotal evidence and by conclusion reached by King (2009, p. 331) in a review of visual influences on auditory spatial learning that “accurate, and even supra-normal, auditory localization abilities can be achieved in the absence of vision.” This also agrees with the observations that blind listeners are at least comparable and usually slightly better than sighted listeners in performing localization task (Ashmead et al., 1998; Lessard et al., 1998; Starlinger and Niemeyer, 1981; Simon et al., 2002). The point of view that general visibility of surroundings is usually not helpful in auditory localization task is further supported by Lewald (2007) who reported that short-term (90 min) light deprivation prior to the localization task improves localization accuracy (but not localization precision; see section 5).

Additional general factors that may affect sound source localization are the listener’s familiarity with the sound source and the listener’s expectations. Various authors have reported that the localization of unfamiliar sounds is worse than that of familiar ones (Blauert, 1974/2001; Brown and May, 2005; Coleman, 1962; Kietz, 1953; Plenge and Brunschen, 1971; Plenge, 1972). This is related to the fact that in order for a listener to take advantage of the fact that the spectrum of an arriving sound depends on the angle of its incidence, the sound must be known to the listener. For example, familiarity with the sound source (e.g., a voice of a particular person) may help to disambiguate potential front-back confusion and determine whether the sound is coming from the front or from the rear. Blauert (1974/2001) cited two studies (Blauert, 1970; Wettschurek, 1971) in which listeners localized familiar and unfamiliar voices in the median plane and reported localization errors of 9° and 17°, respectively. Similarly, sound coloration may indicate whether the sound source is behind another object or in a direct path to the listener. Once the perceived position of the sound source is stored in the listener’s memory, it aids in localization (Han, 1992). The role of familiarity in localization performance also underscores reports that some hearing aid users localize worse with hearing aids than without (e.g., Noble and Byrne, 1990). Yet, despite the plethora of localization cues, some listeners’ expectations are so strong that they can override all the auditory cues. Even if an eagle’s cry is played from a loudspeaker located on the ground (outdoors), most people will still first look to the sky.

2.5 Directional Bands

Since sound source localization in the vertical plane depends greatly on modifications to the sound spectrum by torso and pinna reflections, perceived changes in source elevation can be also produced by deliberate changes in the sound spectrum without moving the physical source (Xu et al., 2000). Blauert (1968; 1969), Middlebrooks and Green (1991), Rogers and Butler (1992), Middlebrooks (1992), and others have demonstrated that for continuous tones and narrow noise bands the perceived location of the sound source in the median plane is not related to the actual position of the sound source but to the dominating frequency of the sound when the head is kept in a fixed position. For example, the sound spectra at the ears for sounds arriving from the frontal, overhead, and rear directions have peaks at around 250–500 Hz and 2–5 kHz, 6–8 kHz, and 0.8–1.6 and 10–12 kHz, respectively (Blauert, 1968; Han, 1991; 1992; Hebrank and Wright, 1974; Itoh et al., 2007; Morimoto and Aokata, 1984; Wright et al., 1974). A schematic view of

the distribution of directional bands along the frequency scale is shown in figure 4. Thus, tones and narrowband noises in the respective bands have a tendency to be localized as arriving from the frontal, overhead, and rear directions regardless of the actual position of the sound source. However, large individual differences are to be expected (Itoh et al., 2007), and the effect mostly disappears for dynamically changing stimuli. Blauert (1969; 1974/2001) used the term *directional bands* to describe this phenomenon and the directions assigned to the specific frequency bands.

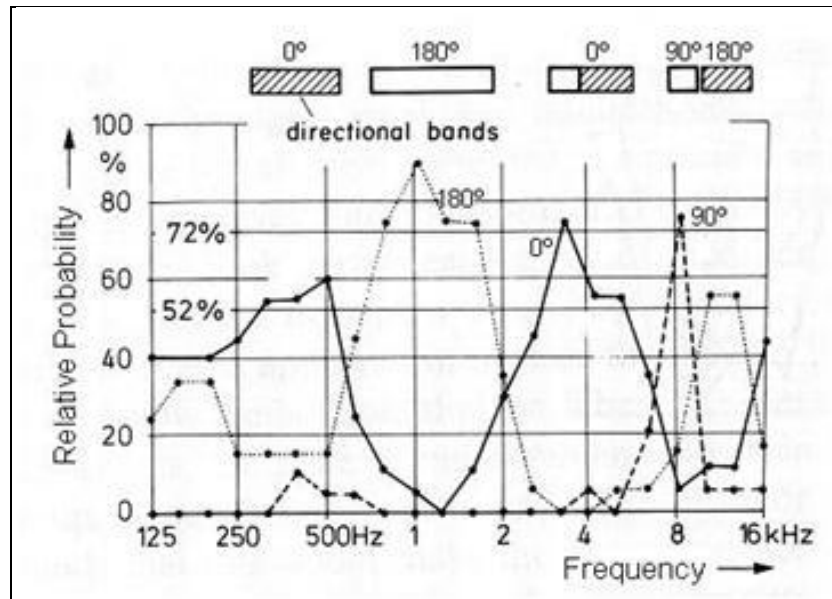


Figure 4. Directional bands in the median plane. The angles 0°, 90°, and 180° indicate front, up, and back directions, respectively. Adapted from Blauert (1974/2001).

It can be hypothesized that reports indicating that harmonic structure is more important for grouping acoustic stimuli in space than their actual spatial proximity (e.g., Buell and Hafter, 1991) may be related to the phenomenon of directional bands.

2.6 Effects of Hearing Loss, Age, and Gender

2.6.1 Hearing Loss

Generally, *asymmetrical* (unilateral) hearing loss decreases localization performance in the horizontal plane (e.g., Comalli and Altshuler, 1976; Hattori, 1966; Häusler et al., 1983; Link and Lehnhardt, 1966; Matzker and Springborn, 1958; Newton and Hickson, 1981; Viehweg and Campbell, 1960). This decrease is always present when peripheral asymmetry is artificially introduced by an earplug and is usually, but not always (see appendix B on localization training), present when the asymmetry is caused by differences between ear sensitivities (Nabelek et al., 1980). In both cases, however, the decrease in performance seems to be worse if the left ear is the “better ear” (Bess et al., 1986; Gustafson and Hamill, 1995). In contrast, *symmetrical*

hearing loss of as much as 30–40 dB has been reported by several authors to have little effect on localization performance in the horizontal plane (e.g., Abel and Hay, 1996; Blauert, 1974/2001; Butler, 1970; Rösner, 1965; Tonning, 1973b). There is a consensus among researchers on the very slight effect of symmetrical sensorineural (high frequency) hearing loss on localization performance. However, a significant decrease in localization performance was reported by some authors in the case of conductive (low frequency) hearing loss (e.g., Gatehouse and Pattee, 1983; Noble et al., 1994; 1997). Noble and his colleagues attributed this finding to the disruption of ITD cues and the increased role of bone conduction in sound transmission to the inner ear (Noble et al., 1994; 1997).

Asymmetrical hearing loss results in large localization errors in the horizontal plane, but even total deafness in one ear allows some degree of horizontal sound source localization (Bochenek and Mitkiewicz-Bochenek, 1963; Tonning, 1973b). It is important to note that with time and experience, the size of localization errors made by people with asymmetrical hearing loss is gradually reduced (Angell and Fite, 1901b; Perrott and Elfner, 1968; Häusler et al., 1983). This may be due to progressively greater use of head movements in directional recognition and greater experience in using new localization cues.

Similarly to reports on the effect of bilateral hearing loss on localization in the horizontal plane, localization in the vertical plane seems to depend on the type of hearing loss. Listeners with bilateral sensorineural (high frequency) hearing loss are reported to perform worse than listeners with conductive hearing loss (Butler, 1970; Noble et al., 1994). However, contrary to localization in the horizontal plane, monaural localization in the vertical plane is barely affected by hearing loss (Angell and Fite, 1901a; Butler, 1970).

2.6.2 Age

In contrast to the very limited effect of the observer's age on visual spatial perception, several authors have reported a noticeable effect of age on auditory localization (e.g., Abel and Hay, 1996; Dobрева, 2010; Hattori, 1966; Link and Lehnhardt, 1966; Matzker and Springborn, 1958; Tonning 1973b; Viehweg and Campbell, 1960). In an extensive study, Abel et al. (2000) investigated the effect of aging on localization in the horizontal plane for 7 groups of 16 listeners, aged 10–81, and reported a decrease in performance as early as in the third decade. Using the categorical localization paradigm (see section 11) and many different arrangements of loudspeakers, they observed decrements in localization performance on the order of 12%–15% across all age groups. The decrease was largest for low frequency noise (i.e., ITD differences) and the smallest for broadband noise (i.e., IID+ITD differences). Similar findings were reported by Babkoff et al. (2002), who reported that the accuracy of ITD-based sound source lateralization declines substantially with age, while IID-based lateralization does not and that the age-related worsening in temporal resolution may affect the performance of auditory localization. These data support the idea presented by Scharf et al. (1976) that the human ability to analyze the frequency content of an incoming signal and localize it on the basis of ITDs are

closely related. In contrast, Savel (2009) found no effect of age on localization acuity (both accuracy and precision; see section 5) or on intrasubject variability for localization of low-frequency noises in the horizontal plane.

Several authors have argued that the age-related decline in localization performance may be due, at least partially, to the confounding effect of age-related hearing loss (e.g., Nordlund, 1964; Terhune, 1974). While this argument cannot be solely dismissed on the basis of the studies discussed in the previous paragraph (several authors used age-corrected norms of normal hearing), several other studies have demonstrated that symmetrical hearing loss in young people does not appreciably affect localization performance as long as the arriving sounds are clearly audible (see section 2.6.1 above), leaving an age-effect as the main source of declining localization performance.

2.6.3 Gender

Nilsson et al. (1973) and Newton and Hickson (1981) found no difference in the auditory localization ability of female and male listeners. Langford (1994) and Saberi and Antonio (2003; 2004) observed some, but small, gender-related differences in the discrimination of ITD and IID cues, with female listeners being somewhat less sensitive and more variable in their performance than male listeners. Larger gender-related functional asymmetries in auditory spatial perception have been reported by Lewald (2004). In a simple pointing task testing monaural sound localization in the vertical plane, female listeners were more precise when listening with the left ear, although male listeners did better with the right ear. This was attributed to sexual dimorphism of the posterior parietal cortex, or planum temporale, both areas known to be involved in spatial auditory functions. These results agree with Savel's (2009) observation that male listeners frequently have asymmetrical spatial acuity, favoring the left-hemisphere. Greater asymmetry in the planum temporale in males than in females has been implicated as one of the potential causes of the asymmetric perception (e.g., Voyer, 1996). More recently, Zündorf et al. (2011) reported that while localization acuity in quiet is not gender-dependent, female listeners have greater difficulty in localizing sound sources in noise environments (cocktail party effect) and are more prone to reversal errors (see section 10).

3. Physiology of Auditory Localization

The acoustic coding of spatial information is the result of the physical spacing of the ears and the filtering properties of the human body, including the torso, head, and pinnae. The spatial cues embedded in the auditory signal are additionally amplified or attenuated in the process of impedance transformation while the auditory stimulus travels from the outer ear to the cochlea. The complex auditory signal reaching the cochlea is sampled and frequency analyzed and finally converted into neural responses that are transmitted to the central nervous system (CNS) by the

bundle of neurons forming the auditory nerve. The neural responses from the left and right ear converge at the binaural neural centers of the CNS that merge the left and right input signals into binaural neural code. A schematic drawing of the auditory pathways of the central nervous system is shown in figure 5. According to Boehnke and Phillips (1999), human localization ability in the horizontal plane is based on the input information received from two broadly tuned spatial channels, as opposed to many direction-specific channels. These two channels occupy the left and right auditory hemifields, respectively, with each extending 30° across the median plane.

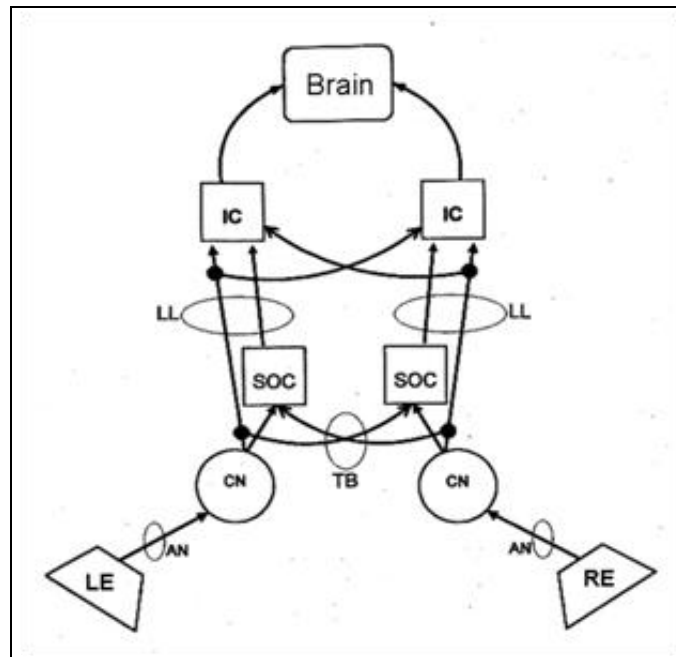


Figure 5. Auditory pathways in the central nervous system. LE – left ear, RE – right ear, AN – auditory nerve, CN – cochlear nucleus, TB – trapezoid body, SOC – superior olivary complex, LL – lateral lemniscus, IC – inferior colliculus. Adapted from Aharonson and Furst (2001).

The auditory fibers leaving the left and right inner ear connect directly to the synaptic inputs of the *cochlear nucleus* (CN) on the same (ipsilateral) side of the brainstem. The CN contains a mass of nerve cell bodies on which nerve fibers form connections and is made of two smaller nuclei: the dorsal cochlear nucleus (DCN) and the ventral cochlear nucleus (VCN). These are formed by type IV cells and bushy cells, respectively (e.g., Shofner and Young, 1985). These types of cells are sensitive to changes in sound intensity, frequency, and onset and offset as well as to the notches in the spectral content of the sound and make up the initial stage of neural processing of auditory stimuli (e.g., Hancock and Voigt, 1999; Imig et al., 2000). The bushy cells of the VCN connect to the ipsilateral *superior olivary complex* (SOC), which is the next processing stage in the auditory pathway. The type IV cells of the DCN bypass the SOC and

connect directly to the ipsilateral *inferior colliculus* (IC) located higher in the processing chain (Davis et al., 2003).

The SOC is the lowest level point in the brainstem where the neural fibers conveying the auditory signals from left and right ear decussate (cross from one side of the nervous system to another) and is the principal site of binaural convergence (King et al., 2001). The SOC receives inputs from both the ipsilateral and contralateral CNs and generates neural signals conveying information about the location of the sound source in the horizontal plane. The SOC consists of four nuclei, but only the medial superior olivary (MSO) and lateral superior olivary (LSO) nuclei receive inputs from both ears. The inputs from the contralateral ear are passed through the *trapezoid body* (TB), which serves as a switch, changing the excitatory signal into an inhibitory signal (Fitzpatrick et al., 2002). The signal switching and processing at the TB level is critical for normal directional hearing. A number of animal studies have demonstrated that the interruption of the neural pathways passing through the TB severely limits an animal's ability to localize sound (e.g., Masterton et al., 1967; Moore et al., 1974).

There are two SOC (the left and the right) in the brainstem, and most of the innervations arriving from one ear terminate at the ipsilateral LSO and contralateral MSO nuclei. The MSO and LSO nuclei are mostly composed of two-input excitatory-excitatory (EE) and excitatory-inhibitory (EI) neuron cells that operate as coincidence and difference detectors (Goldberg and Brown, 1969; Emanuel and Letowski, 2009). These cells are sensitive to binaural differences and perform initial coding of ITDs (mostly in the MSO; Masterton and Diamond, 1967; Brand et al. 2002) and IIDs (mostly in the LSO; Boudreau and Tsuchitani, 1968; Guinan et al., 1972; Irvine et al. 2001; Park, 1998; Yue and Johnson, 1997). Thus, it appears that the MSO and LSO serve as binaural time difference and spectral difference analyzers, respectively (Gatehouse, 1982, p.11). The ITD is encoded by phase/time locking and the IID by a spike rate (Zupanc, 2004).

The projections from the CN and SOC on each side of the brainstem to the ipsilateral IC (see figure 5) form the corresponding *lateral lemniscus* (LL), which is the largest fiber tract in the auditory brainstem. The ICs are where the temporal and spectral pattern information processed in the cochlear nucleus is integrated with the binaural ITD and IID information arriving from the SOC. At the LL/IC level, the auditory pathways re-cross, providing additional coding of binaural information. The importance of this neural bridge, known as the *commissure of Probst*, can be demonstrated, for example, by severing it, which results in a marked decrease in localization performance in the midline plane (Itoh et al., 1996).

The ICs can be considered as the central stage of binaural processing in the brainstem, because all the individual pathways from the CNs, LSOs, MSOs, and LLs terminate at the ICs (Batra and Fitzpatrick, 2002; Casseday and Covey, 1987). Most notable is the further processing of IIDs at the IC level. While LSO processing is sensitive to small IIDs, IC processing is biased toward more global differences (Litovsky et al., 2002; Park, 1998). There are reports indicating that

brain lesions at the SOC level can cause small interaural differences to be perceived as larger ones and that brain lesions at the IC level have the opposite perceptual effect (e.g., Aharonson et al., 1998; Furst et al., 1995; Kavanagh and Kelly, 1992). According to Aharonson and Furst (2001, p. 2850) the SOC “seeks dissimilarity” and the IC “seeks similarity” between the left and right inputs. It has also been hypothesized that the IC is responsible for the existence of the *precedence effect* (e.g., Yin, 1994) and may facilitate both vertical localization and the perception of sound echoes.

The auditory information integrated in the IC is further processed by the superior colliculus (SC) (Oliver and Huerta, 1992; King et al., 2001). Data reported by Middlebrooks and Knudsen (1984) and King and Hutchings (1987) indicate that the topographic representation of auditory space is already developed at the SC level before being remapped at the cortical levels. The final stage of auditory information processing in the brainstem is the *medial geniculate body* (MGB) of the thalamus, which is the entry point of the auditory information to the brain (Starr and Don, 1972; Winer, 1992). From here the signals are projected to the auditory cortex, one on each side of the brain, and recoded to form a spatiotemporal distribution of activity within the brain (Hackett, 2011; King et al., 2001). According to Palomäki et al. (2000) spatial stimuli elicit predominantly contralateral activity in the auditory cortex, and the combined spatial information is processed in the right-hemisphere of the brain.

The high-level bridge between the left and right parts of the nervous system is the *corpus callosum* (CC), which connects the left and right parts of the brain. This late bridge also contributes to overall binaural auditory localization ability (Musiek and Weihing, 2011). However, its disruption is not as detrimental to directional hearing as the disruption of the TB or IC bridges. For example, Lassard et al. (2002) demonstrated that people with callosal agenesis and early callosotomy had greater difficulties with the binaural localization of moving sound sources than listeners in the control group. However, some of the test listeners outperformed the listeners of the control group in localizing stationary sound sources. This was interpreted as indicating that the absence of the CC caused some subjects to make more efficient use of monaural cues. The efficiency of information integration over the CC has been reported to decline to some degree with age (especially during the 40–55 age period) (Bellis and Wilber, 2001), and this may partially explain the observed age-related decline in localization ability discussed in section 2.6.2.

The coding of spatial information at the SOC and LL levels and the decoding of this information in the *auditory cortex* of the brain are the three main neural processes forming our auditory spatial perception (Masterton et al., 1967; Møller, 2000). Recent neuroimaging studies have shown that the processing of auditory spatial information takes place in a distributed network of brain areas including the superior, middle, and inferior frontal gyri and the posterior and inferior parietal and middle temporal cortices (Bushara et al. 1999; Kaiser and Bertrand, 2003; Maeder et al., 2001; Martinkauppi et al., 2000; Weeks et al. 1999). The spike patterns (spike counts and spike timing) of the auditory cortical neurons carry integrated information about sound source

location in both the horizontal and vertical dimensions (Middlebrooks et al., 1994; 1998; Pickles, 2003; Xu et al., 1998; 2000), and some neurons are especially sensitive to this type of information (Middlebrooks and Pettigrew, 1981).

Several authors (e.g., Las et al., 2008; Meredith and Clemo, 1989; Santamaria et al., 2009) have reported that the cortical region of the *anterior ectosylvian sulcus* (AES) plays an important role in facilitating SC response to auditory and visual stimuli. Korte and Rauschecker (1993) and Rauschecker and Korte (1993) observed that after suturing kittens' eyes shut, the kittens developed a smaller visual area and larger auditory area in the AES. The authors hypothesized this may also apply to blind people, who depend greatly on auditory cues (Doucet et al., 2005).

Numerous studies have indicated that the mapping of auditory neural responses to relative coordinates in space is a learned process and that, if needed, this mapping is developed and modified over time (e.g., King et al., 2001). It is also a probabilistic process in which the majority of the neural responses determines the final mapping. Moreover, it is not an isolated process, but rather a synergic one, in which spatial auditory information is moderated by other sensory inputs to the brain, including the sense of balance and various higher order brain processing centers.

4. Terminology, Notation, and Conventions

Depending on the task given to the listener, there are two basic types of localization judgments:

- Relative localization (discrimination task)
- Absolute localization (identification task)

Relative localization judgments are made when one sound source location is compared to another, either simultaneously or sequentially. These judgments are made to determine spatial resolution of events in a given environment or assess the listener's ability to discriminate sounds. Absolute localization judgments involve only one sound source location that needs to be identified. In addition, absolute localization judgments can be made on a continuous circular scale and expressed in degrees ($^{\circ}$) or can be restricted to a limited set of preselected directions. The latter type of judgment occurs when all the potential sound source locations are marked by labels (e.g., number), and the listener is asked to identify the sound source location by label. The actual sound sources may or may not be visible. This type of localization judgment is referred to throughout this report as *categorical localization*.

From the listener's perspective, the most complex and demanding judgments are absolute localization judgments, and they are the main subject of this report. The other two types of judgments, discrimination judgments and categorization judgments, are only briefly described and compared to absolute judgments later in the report.

In order to assess human sound source localization ability, the physical reference space needs to be defined in relation to the position of the human head. This reference space can be described either in the rectangular or polar coordinate system. The rectangular coordinate system x , y , z is the basis of Euclidean geometry and is also called the Cartesian coordinate system. In the human-body-oriented Cartesian coordinate system the x , y , and z axes are typically oriented as left-right (west-east), back-front (south-north), and down-up (nadir-zenith), respectively¹⁴. The right, front, and up directions indicate the positive ends of the scales. The Euclidean planes associated with the Cartesian coordinate system are the vertical lateral (x - z), the vertical sagittal (y - z), and the horizontal (x - y) planes.

In reference to the anatomy of the human body, the relative orientations of the Euclidean planes are shown in figure 6. A sagittal plane is a vertical plane that runs from front to back dividing the body into right and left sections. A lateral plane is a vertical plane that passes from left to right and divides the body into front and back sections. A horizontal plane is a plane perpendicular to the sagittal and lateral planes and divides the human body into superior (upper) and inferior (lower) sections.

The following are the main reference planes of symmetry of the human body:

- Median sagittal (midsagittal) plane: y - z plane
- Frontal (or coronal) lateral plane: x - z plane
- Axial (transversal, transaxial) horizontal plane: x - y plane

The median (midsagittal) plane is the sagittal plane (figure 6) that is equidistant from both ears. The virtual line passing through both ears is called the *interaural axis*. The ear closer to the sound source is termed the ipsilateral ear and the ear farther away from the sound source the contralateral ear. The frontal (coronal) plane is the lateral plane that divides the listener's head into front and back hemispheres along the interaural axis. The axial (transversal) plane is the main horizontal plane of symmetry of the human body, passing through the waist. In the head-centered frame of reference, the axial plane is replaced by the horizontal plane passing through the interaural axis, which is referred to as the *interaural plane*¹⁵. Any references in this report to the horizontal plane refer to the interaural plane.

¹⁴In some publications the x -axis is oriented as front-back and the y axis as right-left (e.g., Gerzon, 1992).

¹⁵Knudsen (1982) refers to the interaural plane as the visuoaural plane.

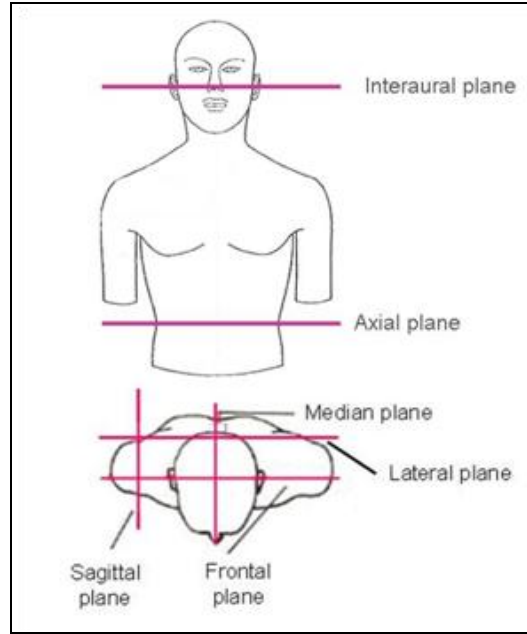


Figure 6. The main reference planes of the human body.

The polar coordinate system can be used both in Euclidean geometry and in the spherical, non-Euclidean, geometry that is useful in describing relations between points on a closed surface such as a sphere. In the polar system of coordinates, the reference dimensions are d (distance or radius), θ (declination or azimuth), and φ (elevation). Distance is the amount of linear separation between two points in space, usually between the observation point and the target. The angle of declination (azimuth) is the horizontal angle between the medial plane and the line connecting the point of observation to the target. The angle of elevation is the vertical angle between the interaural plane and the line from the point of observation to the target. The Cartesian and polar systems are shown together in figure 7.

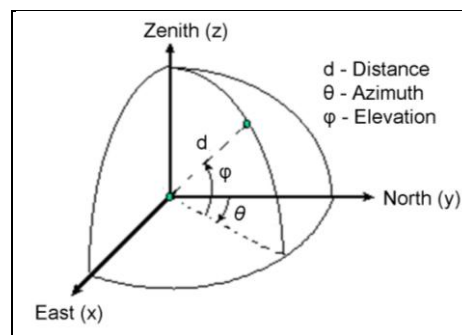


Figure 7. Commonly used symbols and names in describing spatial coordinates.

Although the polar coordinate system based on distance, azimuth, and elevation is almost universally used across the world, and particularly in localization studies, it is not the only

system used. Thus, to differentiate it from other polar systems, it is frequently referred to as the *vertical-polar coordinate system*.

A characteristic property of the vertical-polar coordinate system is that the length of an arc between two angles of azimuth depends on elevation. As a result, the separation distance between N points evenly distributed at a fixed elevation differs depending on the elevation. The points will be closer together near the poles and farther apart near the equator. This means that the points will not be uniformly distributed over the whole sphere. A uniform distribution is desirable, for example, in placing the loudspeakers in 3-D localization studies and selecting the most efficient number of test points in HRTF measurements. In such cases, the separation of points by constant angle of azimuth is not an effective solution.

Another polar coordinate system that is used in auditory localization studies is the *interaural-polar coordinate system* based on distance, lateral angle, and rising angle coordinates (Morimoto, 2001; Morimoto and Aokata, 1984; Morimoto et al., 1983; 2002). The concept of the interaural-polar coordinate system, also referred to as *horizontal-polar coordinate system* (Macpherson and Middlebrooks, 2002), is shown in figure 8.

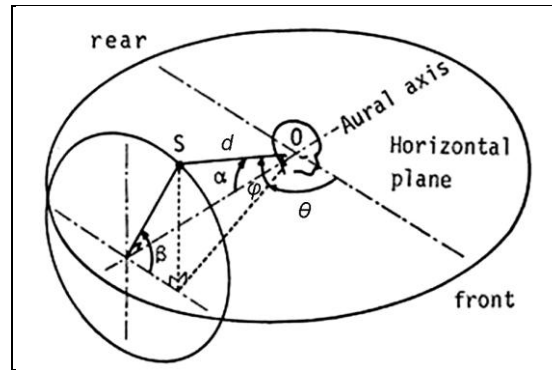


Figure 8. The interaural-polar coordinate system. S – sound source, O – center of the listener's head, d – distance between the sound source and the center of the listener's head; θ – azimuth angle; ϕ – elevation angle; α – lateral angle; and β – rising angle. Adapted from Morimoto and Aokata (1984).

The lateral angle α is the angle between the interaural axis and the direction toward the sound source. The concept of such an angle and the name *lateral angle* was originally introduced by Wallach (1940) in his study of the role of head movement in localization. The *raising angle* β is the angle between the horizontal plane and the plane passing through the interaural axis and the location of the sound source. The lateral angle is frequently referred to as the binaural disparity cue and the rising angle as the spectral cue (Morimoto and Nomachi, 1982; Morimota and Aokata, 1984).

The main advantage of the interaural-polar coordinate system over the vertical-polar coordinate system is that length of the arc (on the surface of the sphere) between two lateral angles is

independent of elevation. However, the interaural-polar coordinate system does not differ from a vertical-polar coordinate system in which the x and z axes have been exchanged. Thus, the length of the arc between two raising angles depends on the lateral angle, which again leads to a non-uniform distribution of points on the surface of the sphere. The difference between both systems can be seen in figure 9.

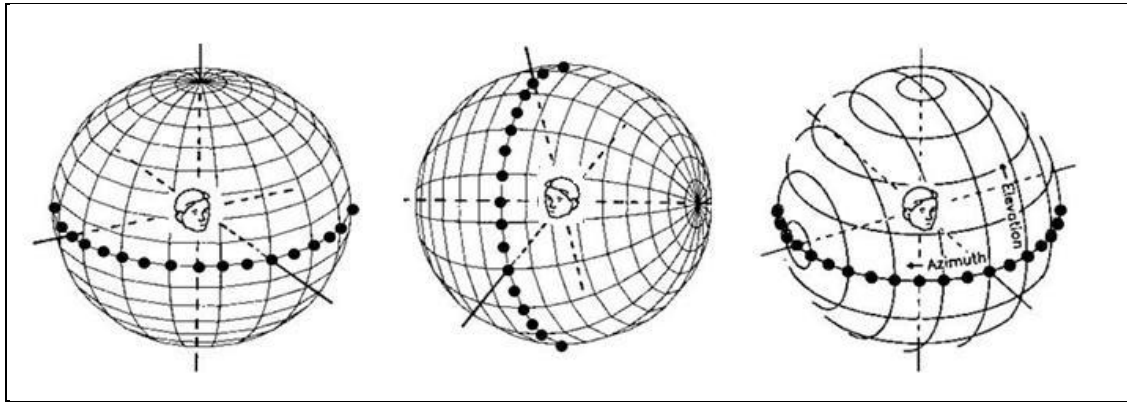


Figure 9. Vertical-polar, interaural-polar, and two-pole coordinate systems (from left to right). Adapted from Carlile (1996).

The vertical-polar and interaural-polar systems are both single-pole coordinate systems, and the interaural-polar system may just as well be called the horizontal-polar coordinate system. However, despite their similar limitations, the interaural-polar system does have an advantage over the vertical-polar system in localization studies since localization resolution in the vertical plane is much poorer than in the horizontal plane.

The polar coordinate system that results in points that are equally separated by angle of azimuth being uniformly distributed over the whole sphere is the *two-pole coordinate system* shown in the right-most panel of figure 9. In the two-pole system, both longitudes and latitudes are represented by a series of parallel circles. Though less intuitive, this system may be convenient for some types of data presentation, e.g., for comparing arbitrary angles and in HRTF studies (Knudsen, 1982; Makous and Middlebrooks, 1990). However, as all three of the systems shown in figure 9 usually share the same concepts of azimuth and elevation, it is essential that the specific spherical coordinate system being used in a study always be explicitly stated (Leong and Carlile, 1998).

It should also be noted that regardless of the polar coordinate system selected, there are two conventions for numerically labeling angular degrees that are used in the scientific literature: the 360° scheme and the $\pm 180^\circ$ scheme. There are also two possibilities for selecting the direction of positive angular change: clockwise (e.g., Tonning, 1970) and counterclockwise (e.g., Pedersen and Jorgensen, 2005).

The use of two notational schemes is primarily a nuisance that necessitates data conversion in order to compare or combine data sets labeled with different schemes. However, converting

angles that are expressed differently in the two schemes from one scheme to the other is just a matter of either adding or subtracting 360° .

In the case of localization studies, in which both average angles and differences between angles are calculated, the $\pm 180^\circ$ labeling scheme is overwhelmingly preferred. First, it is much simpler and more intuitive to use positive and negative angles to describe angular difference. Second, the direct summing and averaging of angular values can only be done with angles that are contained within a (numerically) continuous range of 180° , such as $\pm 90^\circ$, which is very often the whole range of interest. If the 360° scheme is used, or if the continuous range of 180° in a $\pm 180^\circ$ labeling scheme is exceeded, then angles to the left and right of 0° (the reference angle) cannot be directly added and must be converted into vectors and added using vector addition. In the case of angular differences, the angle of 360° must be added to or subtracted from (depending on the notation scheme) the differential angle.

Less clear is the selection of the positive and negative directions of angular difference. However, if the $\pm 180^\circ$ scheme is used, the absolute magnitude of angular values is the same regardless of directionality, which is another reason to prefer the $\pm 180^\circ$ scheme. Under the 360° scheme, the clockwise measurement of any angle other than 180° will have a different magnitude than that same angle measured counterclockwise, i.e., 30° in the clockwise direction is 330° in the counterclockwise direction.

In mathematics (e.g., geometry) and physics (e.g., astronomy), a displacement in a counterclockwise direction is considered positive, and a displacement in a clockwise direction is considered negative. In geometry, the quadrants of the circle are ordered in a counterclockwise direction, and an angle is considered positive if it extends from the x -axis in a counterclockwise direction. In astronomy, all the planets of our solar system, when observed from “above” the Sun, rotate and revolve around the Sun in a counterclockwise direction (except for the rotation of Venus).

However, despite the scientific basis of the counterclockwise rule, the numbers on clocks and all other circular measuring scales, including the compass, increase in a clockwise direction, effectively making it the positive direction. This convention is shown in figure 7 and is used throughout this report. For locations that differ in elevation, the upward direction from a 0° reference point in front of the listener is normally considered as the positive direction, and the downward direction is considered to be the negative direction.

The last potential difficulty in using angular scales is the overlap between horizontal and vertical angular information. To avoid confusion resulting from the simultaneous use of $\pm 180^\circ$ horizontal and vertical coordinates in the vertical-polar coordinate system, the azimuth is specified in the $\pm 180^\circ$ range and elevation in the $\pm 90^\circ$ range. The opposite is true for the interaural-polar coordinate system, resulting in front/back directions expressed as 0° (front) and $+180^\circ$ (back) elevation angles. In the two-pole coordinate system, either of these two conventions can be used but must be clearly specified.

5. Accuracy and Precision of Auditory Localization

Human judgment of sound source location is a *noisy* process laden with judgment uncertainty, which leads to localization errors. Auditory localization error (LE) is the difference between the estimated and actual directions toward the sound source in space. This difference can be limited to difference in azimuth or elevation or can include both (e.g., Wightman and Kistler, 1989b; Carlile et al., 1997). The latter can be referred to as compound LE [or dual-plane error (Laroche, 1994)] and considered as a geometric sum of the horizontal and vertical LEs (e.g., Grantham et al., 2003):

Sound localization error (LE) is the difference between the estimated and the actual direction toward the sound source in space.

Once the localization act is repeated several times, LE becomes a statistical variable. The statistical properties of this variable are generally described by *spherical statistics* due to the spherical/circular nature of angular values ($\theta = \theta + 360^\circ$). However, if the range of the angular judgments is limited to a $\pm 90^\circ$ range, the data distribution can be assumed to have a linear character, which greatly simplifies data analysis (a discussion of statistical analyses is found in sections 6 and 7). Such a situation is typical in the case of auditory localization judgments, where the vast majority of LEs are either *local errors* or *reversal errors*. Local errors, or *genuine errors* (Eyring, 1945), are errors within $\pm 45^\circ$ of the mean, and in practice these will usually stay within $\pm 20^\circ/\pm 25^\circ$ (Carlile et al. 1997; Scharine, 2009). Reversal errors, also called *confusion errors* (Eyring, 1945), can be either front-back or back-front type errors that are larger than $\pm 90^\circ$ and usually close to $\pm 180^\circ$ (Carlile et al., 1997; Scharine, 2005). These errors are a special class of LEs and should be extracted from the whole data set and analyzed separately in order to avoid getting an erroneously large mean localization error (e.g., Bergault, 1991; Carlile et al., 1997; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984a). A more thorough discussion of reversal errors, their effects on mean localization errors, and the methods for accounting for them is offered in section 10. In general, regardless of whether the reversal errors are pre-processed or not, the joint analysis of all types of errors should only be done under specific circumstances and with great caution. This analysis, if performed, should always accompany the separate analyses of both types of errors, since on its own such an analysis may lead to erroneous conclusions. The metrics of linear statistics commonly used to describe the results of localization studies are discussed in section 6. The methods of spherical (circular) statistical data analysis are discussed in section 7.

The probability distribution used to describe localization judgments, and in fact most human judgment phenomena, is the normal distribution, also known as the Gaussian distribution. It is a purely theoretical distribution, but it approximates the distribution of human errors well and is thus commonly used in experiments with human subjects. In the case of localization judgments,

this distribution reflects the random variability of the localizations while emphasizing the tendency of the localizations to be centered on some direction (ideally, the true sound source direction) and to become (symmetrically) less likely the further away we move from that central direction.

The normal distribution has the shape of a bell and is completely described in its ideal form by two parameters: the mean (μ) and the standard deviation (σ). The mean corresponds to the central value around which the distribution extends, and the standard deviation describes the range of variation. In particular, $\sim 2/3$ of the values (68.2%) will be within one standard deviation from the mean, i.e., within the range $[\mu - \sigma, \mu + \sigma]$. The mathematical form and graph of the normal distribution are shown in figure 10.

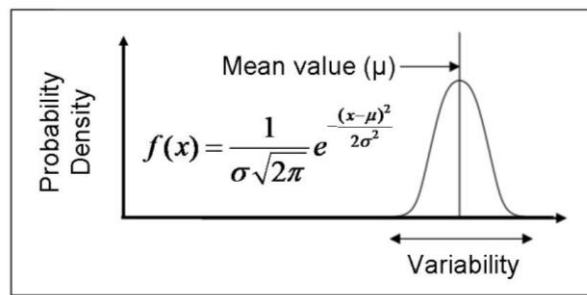


Figure 10. Normal distribution. Standard deviation (σ) is the range of variability around the mean value ($\mu \pm \sigma$) that accounts for $\sim 2/3$ of all responses.

Based on the above discussion, each set of localization judgments can be described by a normal distribution with a specific mean and standard deviation. Ideally, the mean of the distribution should correspond with the true sound source direction. However, any lack of symmetry in listener hearing or in the listening conditions may result in a certain bias in listener responses and cause a misalignment between the perceived location of the sound source and its actual location. Such bias is called constant error (CE). CE depends mainly on the symmetry of the auditory system of the listener, the type and behavior of the sound source (e.g., auditory motion aftereffect¹⁶ (Grantham, 1989; Grantham and Wightman, 1979; Jones and Bunting, 1949; Kagerer and Contreras-Vidal, 2009; Recanzone, 1998), and the acoustic conditions of the surrounding space. It also depends on the familiarity of the listener with the listening conditions and on some non-acoustic factors, such as uneven lighting in the room. Some potential bias may also be introduced by the reported human tendency to misperceive the midpoint of the angular distance between two horizontally distinct sound sources. Several authors have reported the midpoint to be located 1° to 2° rightward (Cusak et al., 2001; Dufour et al., 2007; Sosa et al.,

¹⁶Auditory motion aftereffect (AMA) is a sensation caused by long-term or repeated listening to a sound source moving in one specific direction. After such exposure, a stationary sound source is perceived as moving in the direction opposite to the movement of the previous sound source. According to Neelon and Jenison (2004), AMA is not symmetrical and is much stronger when the adaptor (preceding sound) moves toward the listener's midline. The existence of AMA is considered to be evidence of channel-based spatial coding of information (Hyams and Carlile, 1996).

2010), although this shift may be modulated by listener handedness. For example, Ocklenburg et al. (2010) observed a rightward shift in sound source localization for left-handed listeners and a leftward shift for right-handed listeners (see appendix A).

Another type of error is introduced by both listener uncertainty/imprecision and random changes in the listening conditions. This error is called random error (RE). The size of RE depends primarily on fluctuations in the listener's attention, differences between listeners, and the stability and clarity of the signal emitted by the sound source. In addition, both CE and RE depend on the data collection methodology, especially the form of the listener's response (e.g., direct or indirect pointing, verbal identification, etc.). These forms, called response techniques, are discussed in section 8.

Therefore, LE can be considered as being composed of two error components with different underlying causes: CE resulting from a bias in the listener and/or environment and RE resulting from the inherent variability of listener perception and listening conditions. If LE is described by a normal distribution, CE is given by the difference between the true sound source location (η) and the mean of the distribution (μ) and RE is characterized by the standard deviation (σ) of the distribution. In the case of experimental data, these values are estimated by the sample mean (x_o) and sample standard deviation (SD).

The concepts of CE and RE can be equated, respectively, with the concepts of precision and accuracy of a given set of measurements, although a variety of terms are used in the literature to convey these meanings (e.g., Middlebrooks, 1999ab). The definitions of both these terms, along with common synonyms (although not always used correctly), are given below:

Accuracy (constant error, systematic error, validity, bias) is the measure of the degree to which the measured quantity is the same as its actual value.

Precision (random error, repeatability, reliability, reproducibility, blur) is the measure of the degree to which the same measurement made repeatedly produces the same results.

The relationship between accuracy and precision and the normal distribution from figure 10 are shown in figure 11.

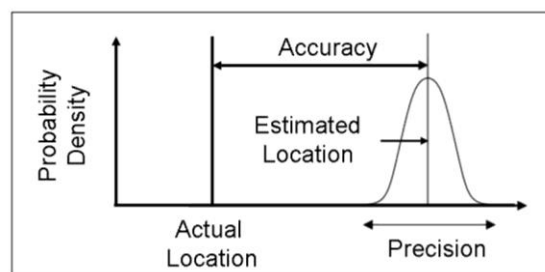


Figure 11. Concepts of accuracy and precision in localization judgments.

The terms “localization accuracy” and “precision” are normally used to characterize the type of error, while the terms “CE” and “RE” are used in reference to the size and value of the error. RE is usually expressed as the SD of the distribution of the localization judgments. There are also several other metrics that can be used to assess RE (see section 6), but SD is the most common RE metric used in the literature. CE can be expressed either as the difference between the mean perceived location (x_o) and the true position of the target (η), which is termed mean error (ME):

$$ME = x_o - \eta, \quad (4)$$

or as the mean error normalized by the *SD* of the responses

$$A = \frac{x_o - \eta}{SD}, \quad (5)$$

where A is the relative ME. This second definition can be interpreted as the relative CE, that is, the ratio of CE to RE, and is a useful metric of the relative contribution of both types of errors to overall LE.

Overall LE, which is sometimes denoted in the literature by the letter D (Hartmann, 1983a; Hartman et al., 1998; Grantham, 1995; Rakerd and Hartmann, 1986), is given by the square root of the sum of the squares of CE and RE:

$$LE = \sqrt{CE^2 + RE^2} \quad (6)$$

It can also be expressed in terms of the goodness-of-fit (GoF) criterion (Bolshev, 2002) as

$$LGoF = \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{(CE^2 + RE^2)}}. \quad (7)$$

Localization goodness of fit (LGoF) is a convenient coefficient to capture the average deviation of the actual localization judgments made over a range of angular sound source positions.

The main problem with using overall LE or LGoF metrics is that these metrics combine two very different types of localization errors, which, when added together, are seldom indicative of anything meaningful. Separate calculations and analyses of CE and RE are almost always more useful for data interpretation and are preferred for data reporting. If, for some reasons, the overall LE is needed, it should always be reported together with the respective CE and RE values.

All the localization error metrics discussed previously - D (overall LE), LGoF, ME, A, and SD - can be used in assessing LE for one specific sound source location or across a range of angular locations by simple spatial averaging, although only the use of RE metrics makes practical sense in the latter case. In addition, since RE is dependent on the angle of incidence of the arriving sound, averaging across several sound source locations makes the most sense when two or more

listening conditions, sound sources, or groups of listeners are being compared rather than as an indicator of the absolute RE for one specific listening situation.

6. Linear Statistical Measures

The two fundamental classes of measures describing probability distributions are measures of central tendency and measures of dispersion. Measures of central tendency, also known as measures of location, characterize the central value of a distribution. Measures of dispersion, also known as measures of spread, characterize how spread out the distribution is around its central value. In general, distributions are described and compared on the basis of a specific measure of central tendency in conjunction with a specific measure of spread.

6.1 Normal (Gaussian) Distribution

For the normal distribution, the mean (μ), a measure of central tendency, and the standard deviation (σ), a measure of dispersion, serve to completely describe (parameterize) the distribution. There is, however, no practicable way of directly determining the true, actual values of these parameters for a normal distribution that has been postulated to characterize some population of judgments, measurements, etc. Thus, these parameters must be estimated on the basis of a representative sample taken from the population. The sample arithmetic mean (x_o) and the sample standard deviation are the standard metrics used to estimate the mean and standard deviation of the underlying normal distribution. The sample arithmetic mean represents the center of gravity of all the numeric judgments. The sample standard deviation, introduced by Pearson (1894) to assess the degree of data concentration, is the square root of the average of the squared deviations of the judgments from their arithmetic mean

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - x_o)^2}, \quad (8)$$

where x_i is the numeric value of the i -th judgment, x_o is the arithmetic mean of all the judgments, and n is the number of judgments.

The sample arithmetic mean is an estimate of the mean value of the population. However, the goodness of this estimation depends on the size of the sample. The smaller the standard deviation of the sample (SD) and the larger the sample size (n), the better the estimate. Thus, a ratio of these two parameters, called *standard error* (SE), and defined as

$$SE = \frac{SD}{\sqrt{n}} \quad (9)$$

is used to estimate how good an estimate of the mean value of the population is to a specific sample arithmetic mean¹⁷.

If the data in the sample are normally distributed, the arithmetic mean x_o and standard error SE can be used to calculate *confidence intervals* for the population mean. A p confidence interval is a range of values, within which the unknown population parameter will be contained with probability p (Yaremko et al. 1986). The most common p value in statistical analysis is $p = 0.95$, which defines the 95% upper and lower limits for the parameter. Since 1.96 is the 97.5 percentile of the normal distribution, the limits of the 95% confidence interval for the mean can be calculated as

$$\text{Upper 95\% limit} = x_o + 1.96 \text{ SE}$$

$$\text{Lower 95\% limit} = x_o - 1.96 \text{ SE.}$$

The sample mean and standard deviation are highly influenced by outliers (extreme values) in the data set. This is especially true for smaller sample sizes. Measures that are less sensitive to the presence of outliers are referred to as robust measures (Huber and Ronketti, 2009).

Unfortunately, many robust measures are not very efficient, which means that they require larger sample sizes for reliable estimates. In fact, for normally distributed data (without outliers), the sample mean and standard deviation are the most efficient estimators of the underlying parameters.

A very robust and relatively efficient measure of central tendency is the median (MD). The median represents the middle point of the data with 50% of the data lying on either side of the median. A measure of dispersion closely related to the median is the median absolute deviation (MEAD), which is the median (middle value) of the absolute deviations from the median. One advantage of the MD and MEAD over x_o and SD is that the former are distribution free and do not need any assumption about the nature of the general population (Gorard, 2005). Similarly to the median, the MEAD is also a very robust statistical measure but is, unfortunately, also very inefficient.

A more efficient measure of dispersion that is, however, not quite as robust is the mean absolute deviation (MAD), which is the average of the absolute deviations from the mean. Note that the abbreviation “MAD” is used in other publications to refer to either of the median and mean absolute deviations (here, MEAD and MAD), which can cause some additional confusion. The formulas for both the standard and robust sample measures discussed previously are given in table 1. They represent the basic measures used in calculating LE when traditional statistical analysis is performed.

¹⁷More formally, SE is an estimator of the true standard deviation of the distribution of the sample means of samples of size n taken from the general population.

Table 1. Basic measures used to estimate the parameters of a normal distribution.

Measure Name	Symbol	Definition/Formula	Comments
Arithmetic mean	x_o	$x_o = \frac{1}{n} \sum_{i=1}^n x_i$	—
Sample standard deviation	SD	$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - x_o)^2}$	V (variance) = SD^2 .
Median	MD	middle value of responses	—
Median absolute deviation	MEAD	middle value of the absolute deviations from the median	—
Mean absolute deviation	MAD	$MAD = \frac{1}{n} \sum_{i=1}^n x_i - x_o $	—

Note: The formula for SD listed in the table is the biased sample SD formula. To provide an unbiased estimate of the population σ the factor $1/n$ should be replaced by $1/(n-1)$.

Strictly speaking, the sample median estimates the population median, which is the midpoint of the distribution, i.e., half the values (from the distribution) are below it and half are above it. The median together with the midpoints of the two halves of the distribution on either side of the median divide the distribution into four parts of equal probability. The three dividing points are called the 1st, 2nd, and 3rd quartiles (Q1, Q2, and Q3), with the 2nd quartile simply being another name for the median. Since the normal distribution is symmetric around its mean, its mean is also its median, and so the sample median can be used to directly estimate the mean of a normal distribution.

The median absolute deviation of a distribution does not coincide with its standard deviation, thus the sample median absolute deviation does not give a direct estimate of the population standard deviation. However, in the case of a normal distribution, the median absolute deviation corresponds to the difference between the 3rd and 2nd quartiles, which is proportional to the standard deviation. Thus, for a normal distribution, the relationship between the standard deviation and the MEAD is given by (Goldstein and Taleb, 2007):

$$\sigma \approx 1.4826(Q3 - Q2) = 1.4826(MEAD) . \quad (10)$$

6.2 Skew and Kurtosis

Skew (skewness) and kurtosis are two parameters of a data distribution that characterize its departure from a normal, bell-like distribution. They are seldom used in auditory localization studies but are useful in quantifying the deviation from normality of a set of localization judgment due to poorly controlled experimental conditions that may change over time or a lack of uniformity (or normality) in the listener panel participating in the study. They are especially useful in assessing hard-to-quantify effects of environmental changes (e.g., wind strength and direction) on localization data collected in the open field.

Skew (S) is a measure of the lack of symmetry and was originally defined by Pearson (Pearson, 1894; 1895; Stuart and Ord, 1994; Wuensch, 2005) as

$$S = \frac{3(x_o - MD)}{SD}, \quad (11)$$

where x_o is the arithmetic mean, MD is the median, and SD is the standard deviation, but was later on re-defined by Fisher (1925) as

$$S = \frac{\sum_{i=1}^n (x_i - x_o)^3}{(n-1)SD^3}, \quad (12)$$

where x_o is the arithmetic mean, x_i is an i -th value in the sample, SD is the standard deviation, and n is the sample size. To differentiate between these two concepts of skew, they are sometimes called *Pearson's skew* (SP) and *Fisher's skew* (SF), respectively. A normal distribution has $S=0$. Skew is negative if more of the data are on the right side and the distribution has a longer left tail. Such a distribution (or sample) is called left-skewed. Skew is positive if more of the data are on the left side and the distribution has a longer right tail. Such a distribution (or sample) is called right-skewed. Note that skewed data can be normalized (made symmetrical) using, for example, the Box-Cox transformation (Box and Cox, 1964) or other nonlinear transformations, which can be found in most statistical handbooks and standard statistical software packages. An important use of these transformations is in outlier detection in skewed data sets, since these are easier to identify in normalized distributions. For further discussion of outliers see section 10.2.

Skew as defined in equations 11 and 112 represents the sample skew. These values can be used as biased estimators of the underlying skew, but they do not work well for small sample sizes (n). For small samples, an unbiased estimator of population skew is given by (Joannes and Gill, 1998)

$$Su = \frac{\sqrt{n(n-1)}}{n-2} SF. \quad (13)$$

The standard error of skew (SES) can be calculated as (Cramer, 1997, p.85; Tabachnick and Fidell, 1996)

$$SES = \sqrt{\frac{6n(n-1)}{(n-2)(n+1)(n+3)}} \approx \sqrt{\frac{6}{n}}. \quad (14)$$

Note that the SES is only a function of n , and it does not depend on any aspect of the shape of the distribution (Wright and Herrington, 2011). If the absolute value of the skew is twice (actually 1.96) as large as the SES or greater, the distribution is considered skewed (95% confidence interval of population skew). This means that the distribution is considered skewed if its skew is significantly different from 0. The common approximation provided on the right side of equation 14 (e.g., Fidell and Tabachnick, 2003, p. 117) is only valid for large n .

Kurtosis (K), from Greek word *kyrtos* meaning bulging, is a measure of the “sharpness” of the distribution and is calculated as

$$K = \frac{\sum_{i=1}^n (x_i - x_o)^4}{(n-1)SD^4} , \quad (15)$$

where x_o is the arithmetic mean, x_i is an i -th value in the sample, SD is the standard deviation, and n is the sample size. The kurtosis of the normal distribution is 3; therefore, equation 15 is frequently adjusted by this value to be

$$K = \frac{\sum_{i=1}^n (x_i - x_o)^4}{(n-1)SD^4} - 3 , \quad (16)$$

so that the normal distribution has a kurtosis of 0. This normalized kurtosis is sometime referred to as *excess kurtosis* and can vary from -2 to $+\infty$. Distributions (or samples) with negative kurtosis (low kurtosis) are called *platykurtic* (flat), those without kurtosis ($K = 0$) are called *mesokurtic*, and those with positive kurtosis (high kurtosis) are called *leptokurtic* (sharp). Platykurtic (flat) distributions have a flatter top and shorter and thinner tails while leptokurtic (sharp) distributions have a sharp top but longer and wider tails. Skewed distributions are always leptokurtic (Hopkins and Weeks, 1990). An unbiased estimator of underlying kurtosis that works well for any n can be calculated as (Joanne and Gill, 1998)

$$Ku = \frac{(n-1)}{(n-2)(n-3)} [(n+1)K + 6] . \quad (17)$$

The standard error of kurtosis (SEK) can be calculated as (Cramer, 1997, p.89)

$$SEK = 2K \sqrt{\frac{n^2-1}{(n-3)(n+5)}} \approx \sqrt{\frac{24}{n}} . \quad (18)$$

Note that the SEK, similarly to the SES, is only a function of n and does not depend on any aspect of the shape of the distribution (Wright and Herrington, 2011). If K differs from 0 by two or more SEKs, the distribution cannot be considered to be mesokurtic (95% confidence interval of population kurtosis). This means that the distribution is considered platykurtic or leptokurtic if its kurtosis is different from 0 with 95% probability. The approximation given on the right side of the equation 18 is again only valid for large n .

6.3 Localization Error Metrics

Skew and kurtosis are effective measures of how far specific sample distributions characterized by the parameters in table 1 depart from the ideal normal distribution. The parameters listed in table 1 are also the basis for calculating LE, CE, and RE. The main metrics used in calculating LE and the related formulas are listed in table 2.

Table 2. Basic metrics used to calculate localization error (η denotes true location of the sound source).

Metric Name	Symbol	Type	Definition/Formula	Comments
Mean Error (Mean Signed Error)	ME	CE	$ME = \frac{1}{n} \sum_{i=1}^n (x_i - \eta) = x_o$	—
Mean Absolute Error (Mean Unsigned Error)	MUE	CE and RE	$MUE = \frac{1}{n} \sum_{i=1}^n x_i - \eta $	$ ME \leq MUE \leq ME + MAD$
Root-Mean-Squared Error	RMSE	CE and RE	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \eta)^2}$	$RMSE^2 = ME^2 + SD^2$
Sample Standard Deviation	SD	RE	$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - x_o)^2}$	—
Mean Absolute Deviation	MAD	RE	$MAD = \frac{1}{n} \sum_{i=1}^n x_i - x_o $	$MAD \approx 1.18$ MEAD

Note: The formula for SD listed in the table is the biased sample SD formula. To provide an unbiased estimate of the population σ the factor $1/n$ should be replaced by $1/(n-1)$.

The formulas listed in table 2 and discussed previously apply to normal or similar unimodal distributions. In the case of a multimodal data distribution, these metrics are in general not applicable. However, if there are only a few modes that are relatively far apart, then these metrics (or similar statistics) can be calculated for each of the modes using appropriate subsets of the data set. This is in particular applicable to the analysis of reversal errors, which tend to define a separate unimodal distribution (see section 10).

SD is the standard metric for RE, while the standard metric for CE is the ME, also called mean bias error, which is equivalent to the difference between the sample mean of the localization data (x_o) and the true location of the sound source. The unsigned, or absolute, counterpart to the ME, the mean unsigned error (MUE) is a metric of total LE as it represents a combination of both the CE and the RE. The MUE was used among others by Searle et al. (1975; 1976) and Makous and Middlebrooks (1990) in analyzing their data. Another error metric that combines the CE and RE is the root mean squared error (RMSE). The relationship between these three metric is given by the following inequality, where n is the sample size (Willmott and Matusuura, 2005).

$$|ME| \leq MUE \leq RMSE \leq \sqrt{n} MUE. \quad (19)$$

For example, Erickson et al. (1991) reported average $MUE = 6.3^\circ$ and $ME = 1.31^\circ$ over a variety of wide- and octave-band stimuli presented at the Air Force's Auditory Localization Facility (ALF).

The RE part of the RMSE is given by the sample standard deviation, but the RE in the MUE does not in general correspond to any otherwise defined metric. However, if each localization estimate is shifted by the ME so as to make the CE equal to zero, the MUE of the data

normalized in this way is reduced to the sample MAD. Since the MAD is not affected by linear transformations, the MAD of the normalized data is equal to the MAD of the non-normalized localizations and so represents the RE of the localizations. Thus, the MAD is also a metric of RE. For a normal distribution, the standard deviation is proportional to the mean absolute deviation in the following ratio (Goldstein and Taleb, 2007):

$$\sigma = \sqrt{\frac{\pi}{2}} MAD \approx 1.253(MAD) . \quad (20)$$

This means that for sufficiently large sample sizes drawn from a normal distribution, the normalized MUE (=MAD) will be approximately equal to 0.8 times the SD. The effect of sample size on the standard deviation of the ratio of the sample MAD and the (uncorrected) sample SD for samples from a normal distribution is shown below in figure 12. It shows that for sample sizes larger than 50 the potential error in determining σ from MAD should not exceed 0.03, that is, 4%.

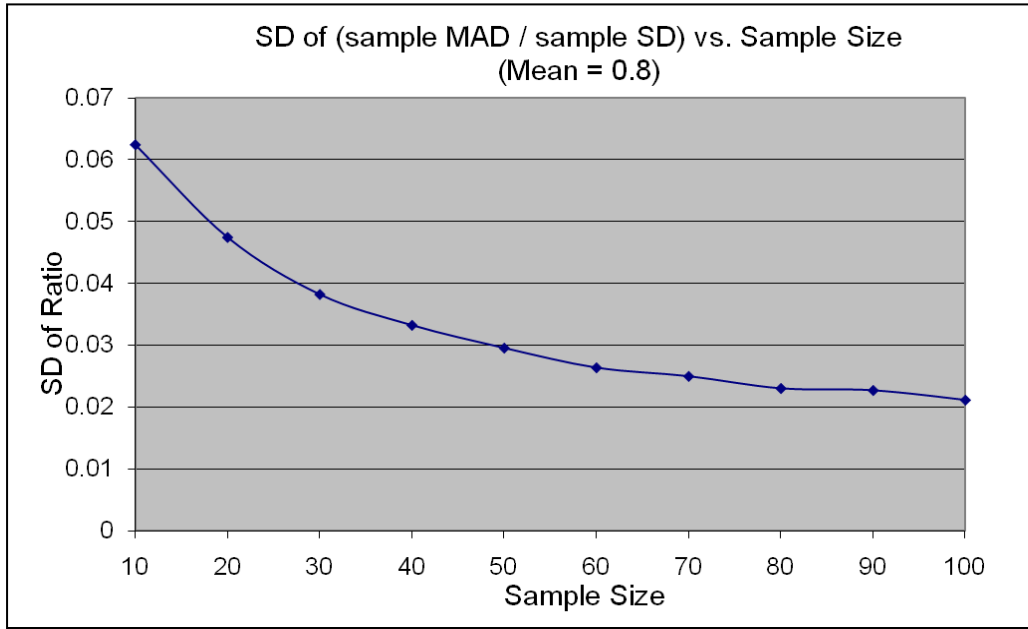


Figure 12. The standard deviation of the ratios between sample MAD and sample SD for sample sizes 10 to 100 generated 1000 times each plotted against the size of the sample.

6.4 Issues Associated with the Application of the Mean and Standard Deviation

The common primacy of the sample arithmetic mean and sample standard deviation for estimating the population parameters is based on the assumption that the distribution is unimodal and relatively symmetrical. This is frequently not the case with human experiments, which have numerous potential sources for data contamination resulting from such factors as an unbalanced composition of the listening panel and inconsistent concentration of the listeners. In general, data collected in such experiments show more values farther away from the mean than expected

(heavier tails or greater kurtosis), are more likely to be multimodal, and contain more extreme values (outliers), especially for smaller data sets.

It is generally desired that a small number of extreme cases should not overly affect the conclusions based on the data. Unfortunately, this may not be the case with the sample mean and standard deviation. As mentioned earlier, the mean and, in particular, the standard deviation are quite sensitive to outliers (the inaccurate results). Their more robust counterparts discussed in this section are a way of dealing with this problem without having to specifically identify which results constitute the outliers, as is done in trimming and winsorizing (see section 10).

Moreover, the greater efficiency of the sample SD over the MAD disappears with only a few extreme cases in a large sample (Huber and Ronchetti, 2009). Thus, since there is a high chance of the underlying distribution not being perfectly normal, the use of more robust metrics for estimating the CE (mean) and RE (standard deviation) may be recommended.

It is also recommended that both components of localization error, CE and RE, always be reported individually. A single compound metric of error such as the RMSE or MUE is not sufficient for understanding the nature of the errors. These compound metrics can be useful for describing total LE, but they should be treated with caution. Opinions as to whether RMSE or MUE provides the better characterization of total LE are divided, although MUE seems to be more commonly used (e.g., Wenzel et al. 1993; Wightman and Kinsler, 1989b). The overall GoF measure given in equation 7 clearly uses RMSE as its base. Some authors consider RMSE as “the most meaningful single number to describe localization performance” (Hartmann, 1983a, p. 1382) and as the type of metric, which “in addition to being sensitive to information across all locations ... is also sensitive to a wide range of changes in the target-response relationship” (Aronoff et al. 2010, p. EL90). However, others argue that MUE is a better measure than RMSE. Their criticism of RMSE is based on the fact that RMSE includes MUE but is additionally affected by the square root of the sample size and the distribution of the squared errors which confounds its interpretation (Willmott and Matusuura 2005).

7. Spherical Statistics

Spherical statistics, called also directional statistics, is a special branch of statistics providing a set of mathematical tools developed to analyze directions in space or positions of points on the surface of a sphere. Such tools are used in several areas of science including astronomy, geophysics, geography, and biological sciences. Although there were several attempts to account for sphericity of spatially distributed data in the past, the science of spherical statistics was started as late as 1953 by R. A. Fisher (1953), who mathematically described distribution of angular errors and provided methodology to calculate basic statistical parameters (mean direction, measure of dispersion) describing such distribution. Since localization data are angular data, spherical statistics has to be used in general case to describe such data.

7.1 Limitations of Linear Statistics when Applied to Sound Localization Data

The analysis of localization data using linear statistics is complicated by the fact that the potential locations of sound sources around a listener form a continuous and circular area. The traditional statistical methods discussed earlier were developed for linear distributions extending from negative to positive infinity. These tools are not, in general, appropriate for the analysis of circular data, such as angles, which wrap around a circle. The circular scale can be considered a special case of an interval scale with no natural zero point and no natural designation of high or low values (Zar, 1999). The fundamental reason linear statistics is not appropriate for circular data is that if the numerical difference between two angles is greater than 180° , then their linear average will point in the opposite direction from their actual mean direction. For example, the mean direction of 0° and 360° is actually 0° , but the linear average is 180° . Even if the differences between angles are smaller than 180° but larger than 90° their arithmetic average has a tendency to be orthogonal to the main axis of the distribution. The result of linear averaging of two angles is additionally dependent on the way the angles are measured (see section 4). For example, the average of the two angles expressed as 90° and 270° in the 360° notation scheme is 180° , but the average of the same two angles in the $\pm 180^\circ$ ($+90^\circ$ and -90°) notation scheme is 0° . Since statistical analysis relies on being able to sum data points, it is clear that something other than standard addition must serve as the basis for the statistical analysis of angular data. The simple solution comes from considering the angles as vectors of unit length and applying vector addition. This vector summation of angular data is the basis of spherical statistics, which provides a basic set of tools for the analysis of circular data.

Spherical statistics is a set of analytical methods specifically developed for the analysis of probability distributions on spheres. Distributions on circles (two-dimensional spheres) are handled by a subfield of spherical statistics called circular statistics. Spherical (circular) data distributions differ from linear distributions and need to be described differently. A circular distribution is a probability distribution whose total probability is confined within the circumference of a circle (Rao Jammalamadaka and SenGupta, 2001). An inherent problem with considering a linear normal distributions statistically in a circular space is that the former is defined on an unbounded domain $(-\infty, +\infty)$, while the latter is defined on a bounded domain $(-180^\circ, +180^\circ)$. Therefore there is a real risk that non-zero probabilities on the normal distribution will fall outside of this range and must be dropped. For example, when a linear normal distribution with $SD=130^\circ$ is wrapped around a circle, almost 20% of the data wraps on top of itself (Cain, 1989). Only when the linear variance of the circular data is sufficiently small (as discussed further) or when the whole data set is mostly confined to a $\pm 90^\circ$ range around a central point can angular data be analyzed as coming from a linear distribution. Under these conditions, the linear distribution fits almost in its entirety onto the circumference of the circle without overlap, and the large errors can be assumed to be outliers¹⁸. In the case of spherical

¹⁸Front-back errors are a special class of errors and are not considered here since they require a separate analysis.

angles, the data points are spread across the surface of the sphere, and linear statistics is not appropriate for summing (averaging) horizontal angles across various elevations or vice versa.

7.2 Theoretical Foundations

In the spherical analysis of auditory localization data, the data are vectors that indicate directions and have no meaningful magnitudes unless the judgments involve distance estimation (an extremely rare situation). Thus, in the general case, localization data can be represented by vectors of unit (1) length each having the same point of origin and terminating at the surface of the unit sphere centered at the point of origin. Each vector can be described by its declination (azimuth) and inclination (elevation), which represent projections of the spherical angle onto the horizontal and vertical planes, respectively. If the auditory localizations are limited to the horizontal plane, the Cartesian coordinates X and Y of the mean vector of a set of judgments (unit vectors) corresponding to specific planar angles θ about the origin are given by

$$X = \frac{1}{n} \sum_{i=1}^n \sin(\theta_i) \quad (21)$$

and

$$Y = \frac{1}{n} \sum_{i=1}^n \cos(\theta_i) \quad (22)$$

The angle θ_o that the mean vector makes with the x -axis is the mean angular direction of all the angles in the data set. Its calculation depends on the quadrant the mean vector is in (Rao Jammalamadaka and SenGupta, 2001):

$$\theta_o = \begin{cases} \arctan(X/Y) & X > 0, Y > 0 \\ \arctan(X/Y) + \pi & Y < 0 \\ \arctan(X/Y) + 2\pi & X < 0, Y > 0 \\ \pi/2 & X > 0, Y = 0 \\ -\pi/2 & X < 0, Y = 0 \end{cases} \quad (23)$$

This angle is frequently called the judgment centroid and is represented by the unit vector with this angle. When $X = 0$ and $Y = 0$, the judgment centroid is undefined. The magnitude of the mean vector is called the *mean resultant length* (R)¹⁹ and is calculated as

$$R = \sqrt{X^2 + Y^2} \quad (24)$$

¹⁹In some books, the mean resultant length is denoted by “ r ,” and $R = nr$, where n is the number of judgments.

R is a measure of concentration, the opposite of dispersion, which plays an important role in defining the circular standard deviation. Its magnitude varies from 0 to 1²⁰ with R = 1 indicating that all the vectors (angles) in the set point in the same direction and R = 0 indicating a uniform dispersion of the vector directions. Note that R = 0 not only for a set of angles that are evenly distributed around the circle but also for a set of angles that are equally distributed between two opposite directions. Thus, like the linear measures discussed in section 6, R is most meaningful for unimodal distributions. However, as opposed to linear measures, circular measures are independent of the way the angles are measured. The graphical representation of θ_o and R is shown in figure 13.

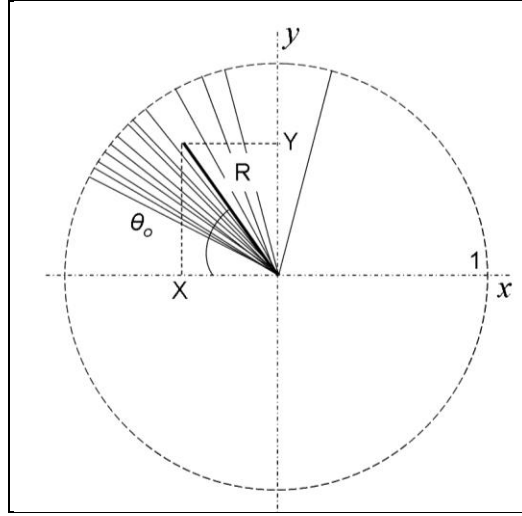


Figure 13. The density distribution of individual judgments and the circular metrics θ_o and R of the judgment distribution. The radii extending from the center of the circle to its circumference represent the individual judgments of direction.

In the case of spherical (3-D) data sets, the previous calculations for θ_o and R take the form:

$$X = \frac{1}{n} \sum_{i=1}^n \sin(\theta_i) \sin(\varphi_i) \quad (25)$$

$$Y = \frac{1}{n} \sum_{i=1}^n \cos(\theta_i) \sin(\varphi_i) \quad (26)$$

$$Z = \frac{1}{n} \sum_{i=1}^n \cos(\varphi_i) \quad (27)$$

and

$$\theta_o = \arctan(Y / X) \quad (28)$$

²⁰In some books X and Y are calculated as sums (not averages), and in these cases, R varies from 0 to n, where n is the number of judgments (e.g., Rao Jammalamadaka and SenGupta, 2001).

$$\varphi_O = \arccos(Z) \quad (29)$$

$$R = \sqrt{X^2 + Y^2 + Z^2} \quad (30)$$

7.3 Circular Distributions

There are a number of theoretical statistical distributions designed to represent circular data. These include the uniform distribution, the wrapped normal distribution (Fisher distribution), and the von Mises distribution. In the case of spherical data, the additional distributions include the von Mises-Fisher distribution (which reduces to the von Mises distribution on a circle) and the bivariate (elliptical) circular normal distribution (Kent distribution). One of these distributions should be referred to when a theoretical distribution is needed to characterized circular or spherical data (Cain, 1989). The differences between the above distributions (save uniform distribution) are rather small, and the user can select whichever distribution is more convenient (Batschelet, 1981; Fisher, 1987; Mardia, 1982). The wrapped normal distribution is additive, has simple trigonometric moments, and leads to tractable measures of variance, skew, and kurtosis. The von Mises distribution is easier to use in hypothesis testing, maximizes entropy, and possesses the maximum likelihood property (Cabot, 1977). In addition, depending on the value of the κ parameter, the von Mises distribution (equation 31) may approximate the wrapped normal distribution (large κ) or reduce to the uniform distribution ($\kappa = 0$). The Kent distribution is preferable in spherical data analysis when the error distribution on the sphere has very different patterns in the horizontal and vertical directions (Leong and Carlile, 1998).

Since the wrapped normal distribution and the von Mises distribution “may be made to approximate each other very closely, it is usually assumed that the two distributions approximately share each other’s properties” (Cabot, 1977, p. 5). Therefore, the selection of one or the other depends on the type of data and the research question. In the case of auditory localization data that can vary from uniform to normal distributions depending on the experimental conditions, the circular data distribution is typically characterized by the von Mises distribution (Fisher, 1996; Fisher et al., 1987):

$$f(\theta, \kappa) = \frac{1}{2\pi I_0(\kappa)} e^{\kappa \cos(\theta - \theta_o)} \quad (31)$$

where θ is the angle, θ_o the mean angle, and $I_0(\kappa)$ the modified Bessel function of order 0:

$$I_0(\kappa) = \frac{1}{\pi} \int_0^\pi e^{\kappa \cos(\theta)} d\theta \quad (32)$$

The κ parameter in the von Mises distribution, as well as other circular distributions, is not a measure of dispersion, like the standard deviation, but, like R, is a measure of concentration. A biased estimator of κ , which is good for large samples, is given by (McFadden, 1980; Tauxe, 2010)

$$\kappa \approx k = \frac{n-1}{n-R} , \quad (33)$$

where n is the sample size, and R is the length of the resultant vector ($0 < R < 1$). An unbiased estimate of κ for small samples ($n < 16$) is given by (Fisher et al., 1987; Wightman and Kistler, 1989b)

$$\kappa \approx k = \frac{(n-1)}{n} \times \frac{(n-1)}{(n-R)} = \frac{(n-1)^2}{n(n-R)} . \quad (34)$$

Frequently, instead of κ , its reciprocal κ^{-1} is reported in scientific literature as it has an interpretation similar to that of the variance (Wenzel et al., 1993). With $\kappa = 0$, the von Mises distribution is equal to the uniform distribution on the circle, and as κ increases the distribution becomes more and more concentrated around its mean. As κ continues to increase, the von Mises distribution begins to more and more closely resemble a wrapped normal distribution:

$$f(\theta) = \frac{1}{\sigma\sqrt{2\pi}} \sum_{k=-\infty}^{\infty} e^{-\frac{(\theta-\theta_0+2\pi k)^2}{2\sigma^2}} , \quad (35)$$

where θ_0 and σ are the mean and standard deviation of the linear distribution.

One of the most significant differences between spherical statistics and linear statistics is that due to the bounded range over which the distribution is defined, there is no generally valid counterpart to the linear standard deviation in the sense that intervals defined in terms of multiples of the standard deviation represent a constant probability independent of the value of the standard deviation (Fisher, 1987). Clearly, as the circular standard deviation increases, fewer and fewer standard deviations are needed to cover the whole circle.

7.4 Circular Standard Deviation

A reasonable approach to defining the circular standard deviation would be to base it on the wrapped normal distribution so that for a wrapped normal distribution it would coincide with the standard deviation of the underlying linear distribution. This can be accomplished due to the fact that for the wrapped normal distribution, there is a direct relationship between the mean resultant length, R (in radians), and the underlying linear standard deviation (Cabot, 1977):

$$R = e^{-\frac{\sigma^2}{2}} . \quad (36)$$

The above equality provides the general definition of the circular standard deviation as (Mardia, 1972)²¹:

$$\sigma_c = \sigma = \sqrt{-2 \ln(R)} . \quad (37)$$

²¹To convert the expressions 35–37 from radians to degrees multiply the result by $180^\circ/\pi$.

If $R \geq 0.82$, equation 37 can be approximated with less than 5% error by (Fisher, 1987)

$$\sigma_c \approx \sqrt{2(1-R)} \quad (38)$$

Circular variance is defined as in the linear case as the square of the standard deviation.

The sample circular mean direction and sample circular standard deviation can be used to describe any circular data set drawn from a normal circular distribution. However, if the angular data are within $\pm 90^\circ$, or within any other numerically continuous 180° range, then linear measures can still be used. Since standard addition applies, the linear mean can be calculated, and it will be equal to the circular mean angle. The linear standard deviation will also be almost identical to the circular standard deviation as long as the results are not overly dispersed. This can be seen in figure 14, in which the circular standard deviation is compared to the linear standard deviation for a set of 500 samples of size 10 and 100.

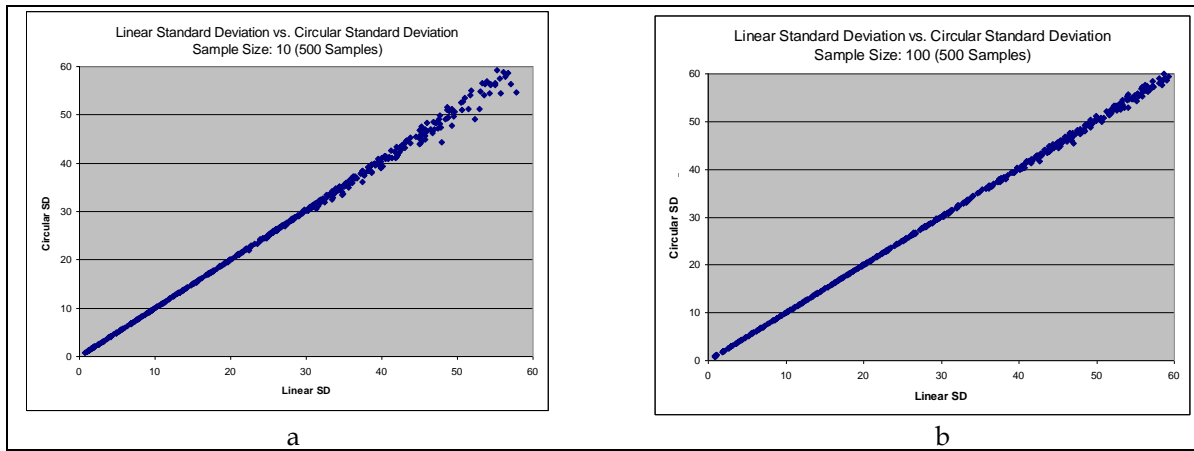


Figure 14. Comparison of circular and linear standard deviations for 500 samples of (a) small ($n = 10$) and (b) large ($n = 100$) size.

The samples were drawn from linear normal distributions with standard deviations randomly selected in the range $1^\circ \leq \sigma \leq 60^\circ$. The two sample standard deviations begin to deviate slightly at about $\sigma = 30^\circ$, but even at $\sigma = 60^\circ$ the difference is not too great for the larger sample size. In fact, the relationship between the linear standard deviation and the circular standard deviation is not so much a function of the range of data as of its dispersion. So, for angular data that are assumed to come from a reasonably concentrated normal distribution, as would be expected in most localization studies, the linear standard deviation can be used even if the data span the full 360° , as long as the mean is calculated as the circular mean angle. It remains strongly advised that, as mentioned earlier, localization errors greater than 120° (reversal errors) should not be excluded from the data set but should be analyzed separately.

7.5 Other Circular Statistics

Once the circular mean has been calculated, the formulas in table 2 in section 6 can be used to calculate the circular counterparts to the other linear error metrics. For example, the spherical (circular) 95% confidence angle, which is an analog of the confidence interval in linear statistics, can be calculated (Fisher et al., 1987, p.131). The determination of the circular median, and thus of the MEAD, is typically a much more involved process. The problem is that there is, in general, no natural point on the circle from which to start ordering the data set. However, a defining property of the median is that for any data set, the average absolute deviation is minimized when calculated with respect to the median, with deviation being the length of the shorter arc between each data point and the reference point. Note that a circular median does not necessarily always exist, as for example, for a data set that is uniformly distributed around the circle (Mardia, 1972). If however, the range of the data set is less than 360° and has two clear endpoints, then the calculation of the median and MEAD can be done as in the linear case.

Circular measures of skew and kurtosis as well as circular regression equations can be also calculated (e.g., Cabot 1977; Mardia, 1972; Rao Jammalamadaka and SenGupta, 2001). However, for data with low variability, they provide results very similar to linear measures, and the linear measures can be alternatively used under the same conditions as mentioned above for the applicability of linear measures to circular data (Batschelet, 1981; Mardia, 1972; Zar, 1999).

In some cases, there are two (or more) angular variables that may be related and their degree of association needs to be determined. For example, in an analysis of the localization judgments performed in the open air, a degree of association between the perceived sound direction and the degree of sound source visibility may be of interest. The degree of association between two circular variables can be measured using circular covariance (Cabot, 1977) or the circular correlation coefficient, $r(x, y)$, defined as (Rao Jammalamadaka and Sarma, 1988; Rao Jammalamadaka and SenGupta, 2001)

$$r(x, y) = \frac{\sum_{i=1}^n \sin(x_i - x_o) \sin(y_i - y_o)}{\sqrt{\sum_{i=1}^n \sin^2(x_i - x_o) \sum_{i=1}^n \sin^2(y_i - y_o)}} , \quad (39)$$

where n is the number of data points, i and j are specific data points, x is the first angular variable, y is the second angular variable, and x_o and y_o are their respective mean values. The value of $r(x, y)$ varies from -1 to 1 , where zero indicates that there is no relationship between the variables, and ± 1 represents identity or reversal between both variables, respectively.

7.6 Circular Data Hypothesis Testing

Both parametric and non-parametric statistical tests can be used to test hypotheses related to circular data. They only require that the angular measurements (judgments) are independent events (Batschelet, 1981). The two basic statistical tests that are used to test for uniformity of

the distribution of circular data are the nonparametric Rayleigh z test and the Rao U_n test. The Rayleigh z test is used to determine whether the data distribution around a circle is sufficiently random to assume a uniform spread of judgments. The zero (H_0) and alternate (H_1) hypotheses of the Rayleigh test are formulated as

- H_0 : the data distribution has no mean direction
- H_1 : the data distribution has mean direction.

If hypothesis H_0 is rejected, this means that the data set has a calculable mean value regardless of the underlying distribution. The Rayleigh test examines the length of the mean vector R in relation to the size, n , of the data set. The test statistic z is formed as

$$z = nR^2. \quad (40)$$

In the case of localization data, n is the number of judgments and R is the measure of the angular spread of judgments (mean resultant length). Critical values of the Rayleigh z value can be found in some statistics books, e.g., Zar (1999, table B.34).

Note that the Rayleigh z test fails when the distribution is multimodal (e.g., bimodal). Such a distribution may be falsely determined to be uniform although all the data may be concentrated at just two or three locations. This may be the case when there is a large percentage of reversal errors in the data set. Jones and James (1969) and Mardia (1972) discuss bimodal distributions and some numeric methods that can be used in describing such distributions. However, in the case of localization judgments, such descriptions need to be supplemented by separate analyses of both parts of the overall distribution.

When all the angles in bimodal distribution are concentrated at the opposite azimuths and are highly concentrated such distribution is called *diametrically bimodal circular distribution*. One convenient method of calculating the mean angle of such bimodal distribution is *angle doubling*, which has an effect of folding the data. In this method, each angle is doubled and if all doubled angles are smaller than 360° than above described vector-based procedure to calculate the mean angle can be used. If the doubled angle is larger than 360° , then 360° are subtracted from this angle prior to adding it to averaging procedure (e.g., Marr, 2011).

The unimodal limitation of the Rayleigh z test does not apply to the Rao U_n test of uniformity (Rao Jammalamadaka and SenGupta, 1972), which tests the hypothesis of a uniform distribution (H_0) against the hypothesis of single or multimodal distribution (H_1). In the Rao test, all the observations θ_i are arranged in increasing order, and the angular distances between successive observations are calculated and compared against the average angular distance $\theta_o = 360^\circ/n$. The sum of absolute deviations from θ_o is used as the test statistics

$$U_n = \frac{1}{2} \sum_{i=1}^n |\theta_i - \theta_o|. \quad (41)$$

Small values of U_n indicate a uniformly distributed data set. Critical values of the Rao U_n statistics can be found, for example, in Rao Jammalamadaka and SenGupta (1972).

In some practical cases, it is useful to test whether the sample data are oriented in a specific predetermined direction. For example, if the investigator has reasons to expect, in advance, that the data set will be oriented toward a specific direction and would like to test this prediction (Zar, 1999). This hypothesis can be tested using the V test (Greenwood and Durand, 1955; Durand and Greenwood, 1958) with H_0 and H_1 hypotheses:

- H_0 : the population data are randomly distributed in reference to the predicted direction
- H_1 : the population data are not randomly distributed in reference to the predicted direction

The test statistic V is a modified Rayleigh z statistic and is computed as

$$V = nR \cos(\theta_o - \theta_{pred}) \quad (42)$$

and the critical value u is calculated as

$$u = V \sqrt{\frac{2}{n}} \quad (43)$$

The critical values of $u(\alpha, n)$ are available, for example, in Zar (1999, table B-35).

The Rayleigh, Rao, and V tests can be considered to be tests of the significance of the mean and do not require any assumptions, except for unimodality in the case of the Rayleigh test, about the underlying distribution. They can be used to test for the lack of a single modality, the lack of any modality, or the lack of a specific modality in the data set, respectively.

To test whether a given theoretical distribution is supported by evidence from the data set, the nonparametric Kuiper test (modified Kolgomorow-Smirnow test) or Watson *one sample* U^2 test can be used (Kuiper, 1962; Mardia, 1972; Zar, 1999). The Watson *two sample* U^2 test can be used to compare two data distributions. The Watson two-sample U^2 statistic is calculated as (Watson, 1962):

$$U^2 = \frac{n_1 n_2}{N^2} \left[\sum_{k=1}^N d_k^2 - \frac{\left(\sum_{k=1}^N d_k \right)^2}{N} \right] \quad (44)$$

where $N = n_1 + n_2$, n_1 and n_2 are the two sample sizes, $d_k = i/n_1 + j/n_2$, and i and j are the respective ranks of the specific angular values within each sample. Critical values of the Watson U^2 test and many other statistical tests, both parametric and nonparametric, that are applicable to circular data can be found in many advanced statistics books (e.g., Batschelet, 1981; Mardia, 1972; Zar, 1999; Rao Jammalamadaka and SenGupta, 2001). For example, the nonparametric homogeneity test known as the Wheeler-Watson-Mardia (WMM) test (Batschelet, 1981; Jin et

al., 2004) can be used to measure the similarity of two different horizontal and vertical angular data distributions. The special-purpose Oriana (<http://www.kovcomp.co.uk>) statistical package provides direct support for circular statistics. Other statistical software that supports circular and spherical statistical analysis includes SAS macros (e.g., Kölliker, M. 2005), a MATLAB Toolbox for Circular Statistics (Berens, 2009), and CircStat for S-Plus, R, and Stata (e.g., Rao Jammalamadaka and SenGupta, 2001).

Finally, regardless of whether the localization data are analyzed using circular (spherical) or alternative linear statistics, it is not sufficient to report only the significance level (p -value) of the measured effect. The p -value only tells whether the sample size n is large enough to state that a given value is statistically different from a certain criterion, but it does not tell by how much. Almost any trivial difference can be statistically significant if the sample size is large enough. Similarly, the size of the observed effect may be quite large, but due to a small sample size, the effect may be not statistically significant. Therefore in all cases, whether or not the test results are statistically significant, it is important to calculate and report a standardized measure of the *effect size* (Hedges, 2007). Such measures include measures of association (e.g., Pearson r , coefficient of regression), measures of difference between groups (e.g., Cohen's d , Hodges' g), and odds ratios. Most of these measures have linear, circular, and linear-circular variants that can be used depending on the type of the data set (Batschelet, 1981, pp. 184–196).

8. Localization Discrimination

Localization discrimination is a relative judgement of the spatial location of one object in reference to another. The basic metric of relative localization ability of the listener is the minimum audible angle (MAA). The MAA is the minimum detectable difference in azimuth (or elevation) between locations of two identical but not simultaneous sound sources²² (Mills, 1958; 1972; Perrott, 1969). In other words, the MAA is the smallest perceptible difference in the position of a sound source. It indicates the “resolution” of the auditory localization system. The MAAs for pure tones measured at various directions of incoming sound are shown in figure 15.

²²In some MAA studies the second stimulus starts before the end of the first one (e.g., Perrott and Pacheco, 1989).

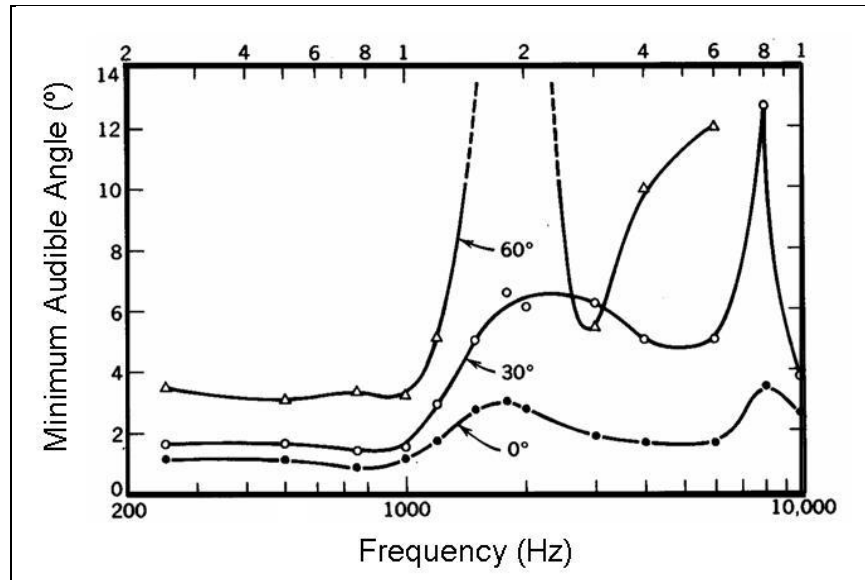


Figure 15. MMAs for pure tones measured at various directions of incoming sound. Adapted from Mills (1958).

To measure the MAA, the listener is presented with two successive sounds coming from two different although nearby locations in space and is asked to determine whether the second sound came from the left or the right of the first one. Since both locations are in close proximity, the CE of the two sound source positions is constant and can be subtracted out. Thus MAA does not include any CE and is only a measure of RE (e.g., Hartmann, 1983a).

The MAA is calculated as half the angle between the minimal positions to left and right of the sound source that result in a 75% correct response rate. It depends on both the frequency and the direction of arrival of the sound wave. For wideband stimuli and low frequency tones, the MAA is on the order of 1° to 2° for the frontal position (Mills, 1958; 1972; Perrott and Saberi, 1990), increases to 8 – 10° at 90° (Kuhn, 1987), and decreases again to 6 – 7° at the rear (Blauert, 1974/2001; Mills, 1958; Perrott, 1969). For low frequency tones arriving from the frontal position, the MAA corresponds well with the difference limen (DL) for ITD (~ 10 – $20 \mu\text{s}$) (Yost and Hafter, 1987), and for high frequency tones, it matches well with the difference limen for IID (0.5 – 1.0 dB), both measured by earphone experiments. The MAA is largest for mid-high frequencies, especially for angles exceeding 40° (Mills, 1958; 1960; 1972). The size of the MAA also depends on the duration of the interstimulus interval (ISI) between the onset of the first and second stimulus. As the ISI increases, the MAA initially decreases and becomes ISI-independent for durations exceeding 100 – 150 ms (Perrott and Pacheco, 1989; Strybel et al., 2000). An ISI duration of 100 – 150 ms may be interpreted as the minimum time needed for the resolution of two spatially different sound sources (Perrott and Pascheco, 1989). This time agrees quite well with the 150 – 200 ms minimum switching time reported by Blauert (1972) for the resolution of a “ping-pong” effect presented to the listener through earphones.

The vertical MAA is about 3° – 9° at frontal position for sound sources in the median plane (e.g., Blauert, 1974/2001; Perrott and Saberi, 1990). However, Grantham et al. (2003) reported that only 6 of their 20 listeners produced a vertical MAA of less than 10° for wideband noise signals recorded through Knowles Electronic Manikin for Acoustic Research (KEMAR) ears and played to the listeners through insert earphones. Perrott and Saberi (1990) and Saberi and Perrott (1990) also measured MAAs for sound sources aligned in several diagonal planes in front of the listener and reported that they remained similar (within 1°) to those measured at the 0° plane until the angle of the plane increased above 80° . The authors concluded that the MAA for frontal positions is practically independent of the plane of presentation until the plane becomes nearly vertical. This observation does not hold for the rear hemisphere, where MAAs at the 60° plane were almost twice as large as those measured in the frontal hemisphere (Saberi et al., 1991a). In contrast, Grantham et al. (2003) reported slightly (but significantly) larger MAA values (about 3°) in the diagonal direction (60°) than in the horizontal plane (about 1.5°) and even larger values in the vertical direction (about 6°). Their data, as well as those of Saberi et al. (1991a) but not of Perrott and Saberi (1990) and Saberi and Perrott (1990), are consistent with the hypothesis that the compound LE (see section 5) is based on independent contributions of the horizontal and vertical LEs. Further studies are needed to resolve this issue.

The MAA has frequently been considered to be the smallest attainable precision (difference limen) in absolute sound source localization in space (e.g., Hartmann, 1983a; Hartmann and Rakerd, 1989a; Recanzone et al., 1998). However, the precision of absolute localization judgments observed in most studies is generally much poorer than the MAA for the same type of sound stimulus. For example, the average error in absolute localization for a broadband sound source is about 5° for the frontal and about 20° for the lateral position (Hofman and Van Opstal, 1998; Langendijk et al., 2001). Thus, it is possible that the MAA observed in these studies, where two sounds are presented in succession, and the precision of absolute localization, where only a single sound is presented, are not well correlated and measure two different human capabilities (Moore et al., 2008). This view is supported by results from animal studies, indicating that some types of lesions in the brain affect the precision of absolute localization but not the MAA (e.g., May, 2000; Young et al., 1992). In another set of studies, Spitzer and colleagues (Spitzer et al., 2003; Spitzer and Takahashi, 2006) observed that barn owls exhibited different MAA performance in anechoic and echoic conditions while displaying similar localization precision across both conditions. The explanation of these differences may be the difference in the perceptual tasks and the much greater difficulty of the absolute localization task. In contrast, Recanzone et al. (1998) observed that absolute localization performance can be predicted from the slope of the psychometric function obtained in the MAA experiment (but not from the MAA value itself).

The MAA in synthetic environments (earphones with HRTF sound synthesis) are generally much larger than those reported for the natural sound field. The horizontal virtual MAA at 0° azimuth was reported to be on the order of 5° – 10° , and the vertical virtual MAA on the order of 15° – 35°

(McKinley and Ericson, 1997; Wersényi, 2007). However, the size of virtual MAAs depends on the quality of the rendered space and the type of earphones used for the study (e.g., circumaural earphones versus insert earphones).

9. Absolute Localization

Absolute localization is the identification of the direction of an incoming sound in absolute terms, i.e., without using a previously heard sound as a reference point. As opposed to the localization discrimination task, LE in the absolute localization task contains both error components: CE and RE (e.g., Hartmann, 1983a). Unfortunately, in many reports, LE is only reported as either MUE or RMSE, and the relative contributions of CE and RE are typically not reported (e.g., Wenzel et al., 1993; Wightman and Kistler, 1989b).

The sizes of CE and overall LE (CE together with RE) as reported in various absolute localization studies differ considerably across the studies. This is caused by the fact that CE is dependent on the asymmetry and specific character of the surrounding environment; the asymmetry of the listener's reception mechanism; and the asymmetry of any potential headgear worn by the listener. The size of both the absolute CE and RE is also dependent on stimulus duration and its temporal (impulsive) properties (Iwaya et al., 2003; Pollack and Rose, 1967; Roffler and Butler, 1968b). These effects are more pronounced in the vertical than horizontal plane. In addition, both CE and RE strongly depend on the signal type used in the study. The largest CEs in the horizontal and vertical planes have been reported for pure tones, and their size decreases with increasing bandwidth and complexity of the emitted sound (Blauert, 1974/2001; Jacobsen, 1976). In contrast, localization acuity does not seem to be affected by the temporal cues provided by amplitude modulation of the target sound (Eberle et al., 2000) and is well maintained at various levels of sustained acceleration (Nelson et al., 2001).

In general, CE is the smallest for frontal positions and increases with sound source laterality and elevation. The largest localization errors have been observed for sound source positions behind the listener, especially for sound sources not located on the listener's interaural plane. For frontal positions and wideband sounds, the reported CEs have been as small as 2° – 4° in azimuth and 3.5° – 4° in elevation (Bauer and Blackmer, 1965; Best et al., 2009; Carlile et al., 1997; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984a; Razavi, 2009) and as large as 10° – 15° in azimuth (Makous and Middlebrooks, 1990; Tiitinen et al. 2004; Tonning, 1970) and 15° – 20° in elevation (Bauer and Blackmer, 1965; Tiitinen et al. 2004). For lateral horizontal positions, they are on the order of 10° , and for rear horizontal positions they can be as large as 20° – 25° (e.g., Blauert, 1974/2001; Oldfield and Parker, 1984a; Rakerd and Hartmann, 1985). Savel (2009) observed that CE in the horizontal plane (low frequency bands of noise, 50 listeners) has a tendency to increase linearly or logarithmically with the laterality of the sound source. She also reported that 58% of her listeners showed a judgment bias toward the medial

axis. Such an overwhelming bias toward the medial axes was also reported in earlier studies (e.g., Sandel et al., 1955; Wells and Ross, 1980). Nevertheless, Savel (2009) also reported that 21% of her listeners demonstrated bias toward the interaural axis. Tonning (1970) and Oldfield and Parker (1984a) observed that CE in the horizontal plane is the smallest at 30° and 330° and the largest at 120°–160° and 200°–240° with respect to the listener's front. Relatively large CEs at 120° and 240° in both the horizontal and frontal planes were also reported by Wilska (1938). That the smallest CEs were observed at 30° and 330° may be related to the fact that in this angular range, especially at 50° and 310°, the pinna works as a parabolic reflector, greatly amplifying incoming sounds (Kuhn, 1987).

Many authors reported that accuracy of absolute localization increases with the increase in the signal bandwidth (e.g., Blauert, 1974/2001; Burger, 1958; Butler, 1986; Middlebrooks, 1992). For example, Shigeno and Oyama (1983) compared localization accuracy of white noise pulses, speech, and pure tone signals in the horizontal plane and reported the largest CE for pure tones and the smallest for white noise pulses. For sound sources located close to the midline, the size of the error has also a tendency to increase with frequency. For example, Pierce (1901) reported a LE of 10° and 20° at 125 Hz and 2–5 kHz, respectively. This monotonic relationship between LE and frequency does not hold, however, for lateral angles, that is, for sound sources not located on the median plane (e.g., Giguère and Abel, 1993). In general, most reports indicate that listeners tend to overestimate the actual lateral position of sound sources located at angles larger than 30° by 5°–15° in both natural (Oldfield and Parker, 1984a) and virtual environments (Carlile et al., 1997; Majdak et al., 2010). In contrast, Perrott et al. (1987) reported that their listeners had a tendency to underestimate the lateral positions of the sound sources. However, they assumed that this tendency was the results of the specific head movement response (HMR) technique used in their study rather than a characteristic property of the auditory spatial function.

Dobbins and Kindick (1967) studied LE in the horizontal plane in a jungle environment and observed that the size of the CE varied with the direction toward the actual sound source but not as much with the type of the emitted sound (pure tones, real-life noises, impact and impulse sounds). The errors were largest for lateral angles (25–30°) and smallest for the frontal direction (15–20°). For lateral angles, the errors tended to be in the direction of the closer ear, while for sound sources located in the frontal plane, they tended to be toward the front of the listener. Caelli and Porter (1980) evaluated drivers' ability to determine the direction of an incoming emergency vehicle's hee-haw siren and reported a CE of 20°. In a similar study, Bauer (1953) investigated listeners' ability to determine the azimuth of the approach (or departure) of a low-altitude-flying and invisible (obscured by vegetation) UH-1B helicopter. He reported an absolute mean localization error (MUE) of 9° for experimental conditions in which the sound of the helicopter was clearly audible. The use of a steel helmet (M1) did not affect localization precision.

The presence of noise greatly degrades localization performance and affects the directional detection threshold (DDT) of sound arriving from an unknown direction (Carhart et al., 1969;

Good and Gilkey, 1996; Kock, 1950). For a speech sound source located in the horizontal plane, a signal-to-noise ratio (SNR) of about -9 to -6 dB is needed for the source to be reliably detected in the presence of diffuse background noise and localization performance increases almost linearly with increasing SNR, reaching its maximum resolution at SNRs of 8 – 12 dB (e.g., Abouchacra et al., 1998a; Abouchacra and Letowski, 2001; Canévet, 1985; Hirsh, 1950; Jacobsen, 1976). Similar data were reported for click signals (Good and Gilkey, 1996; Lorenzi et al., 1999). When a noise sound source is directional, and the target sound and noise masker originate from different locations, the DDT improves by as much as 16 – 20 dB for non-speech and 13 – 15 dB for speech targets in comparison to the situation when the locations of masker and maskee coincide (Abouchacra et al., 1996; 1998b; Good et al., 1997; Saberi et al., 1991b). The spatial distribution of the target and distracting speech sound sources also affects speech intelligibility of the target speech (cocktail party effect). For example, Ricard and Meirs (1994) reported that when the speech signal and directional masker are presented from different directions (30° or more apart) in an AVR, the increase in speech intelligibility is equivalent to about a 4 -dB improvement in SNR. Special tests developed to measure the intelligibility of a target speech signal produced in the presence of other, spatially separated, speech sources include the Coordinated Measure Response (CMR) and the Synchronized Sentence Set (S^3) tests (Abouchacra et al., 2009; 2011; Bolia et al., 2000; Ericson and McKinley, 1997; Moore, 1981).

Sounds presented simultaneously with or shortly preceding the target signal induce both bias and variability in target localization response. Such sounds were once considered as *reference sounds* or *acoustic cues* that could improve localization accuracy. However, the opposite is true and such sounds behave as distracters (Kopčo and Shinn-Cunningham, 2001). The perceived location of the target sound source may be either “attracted toward” or “repulse away from” the distracter location depending on the position of both sound sources and the stimuli characteristics, such as frequency (Butler and Naunton, 1962; Good and Gilkey, 1996; Kashino and Nishida, 1996; Kopčo et al. 2007). It is also possible that the spatial memory of a short sound produced by the target sound source within the background of other spatialized sound sources may be biased toward the center of the quadrant in which the target sound source was located; an effect observed in visual localization studies (e.g., Fitting et al., 2007). Abouchacra and Letowski (2001) presented simultaneous speech (target) and noise (distracter) sound sources that were spatially separated and observed that listeners had a tendency to hear the speech source as coming from a more lateral location than it was actually in, and this effect was observed regardless of the positions of the noise source. The opposite shifts toward the median plane were observed in earlier studies by Sandel et al. (1955) and Butler et al. (1967). Getzmann (2003) examined the effect of distracters on the localization of target sound sources in both the horizontal and vertical planes and reported that the presence of a distracter caused listeners to shift the position of the perceived target sound source away from the distracter in both planes, but that this “contrast effect” was stronger in the vertical plane. Under some conditions, the perceived location of the target sound source is shifted away from the position of the distracter even when the distracter’s sound terminates prior to the presentation of the target sound. Similar

tendencies were reported by Lorenzi et al., (1999) and Kopčo et al. (2001). In contrast, several other authors reported the listener's tendency to judge the location of the sound source as shifted toward the position of the noise source (e.g., Good and Gilkey, 1996; Good et al., 1997; Langendijk et al., 2001; Massaro et al., 1976). These contradicting results are most likely due to the differences in the number of positions of the target sound source used in various studies and the similarity between the target sound and the distracter.

When the preceding sound (cueing sound) arrives exactly from the same direction as the future target sound, target localization performance improves in comparison to the no-cueing control condition (Braasch and Hartung, 2002; Canévet and Meunier, 1994; 1996; Carlile et al., 2001; Thurlow and Jack, 1973b). Getzmann (2004) and several previous authors attributed this effect to the presence of auditory spatial adaptation. In another study, Langendijk et al. (2001) observed that target sound source location uncertainty (LE) increased with increasing number of distracters (from 0 to 2) and, for a single distracter, with decreasing horizontal angular distance between the target and distracter. The increased LE was due to both types of errors: increased uncertainty of the target location (RE) and attraction to or confusion with the distracters (CE). Though the angular distance between the target and distracter had no systematic effect in the vertical dimension, LEs increased substantially for target elevations exceeding 30° when distracters were present.

Several authors have also assessed the minimal distance that can be distinguished between two sequentially presented sounds, e.g., target and masker, but these studies belong to the group of studies discussed in section 8.

Absolute localization performance in the vertical plane depends on the presence of monaural (pinna) cues, sound complexity, and high frequency spectral sound content (Pierce, 1901; Roffler and Butler, 1968b). Typical localization errors are on the order of 4° for a broadband noise source to 10° for a speech source (Damaske and Wagener, 1969; Gilkey and Anderson, 1995; Wettschurek, 1971). They can be as large as 15°–20° for pure tones and narrowband noises. The size of the error increases with greater vertical deviations from the horizontal plane as well as for locations behind the listener. Strybel et al. (1992a) found LE in the vertical plane to be largest at 80° of elevation. In addition, Davis and Stephens (1974) observed that the vertical mean absolute error (MUE) decreased monotonically as sound intensity increased from a 10-dB sensation level (SL) to a 70-dB SL reaching a plateau at about 3.5° at a ~50–60 dB SL. The differences in the size of the localization error between a 20- and 50-dB SL (experiment 1) and a 10- and 30-dB SL (experiment 2) were statistically significant. A similar dependency between sound intensity and localization performance was reported by Altshuler and Comalli (1975) and Comalli and Altshuler (1980).

Short impulse sounds (< 30 ms) are especially poorly localized in elevation, which leads to front-back overhead confusions (Hartmann and Rakerd, 1993) and a general negative shift in perceived elevation toward the horizontal plane (Best et al., 2009; Hofman and Van Opstal,

1998; Macpherson and Middlebrooks, 2000; Vliegen and Van Opstal, 2004). In addition, the magnitude of the negative CE increases with increasing signal level (Brungart and Simpson, 2008; Hartmann and Rakerd, 1993; Macpherson and Middlebrooks, 2000), although Vliegen and Van Opstal (2004) reported that in their study the observed CE was not a monotonic function of sound level and was lowest for a 40–50 dB SL.

Pedersen and Jorgensen (2005) reported that the size of CE in the median plane depends on the actual sound source elevation and is about $+3^\circ$ at the horizontal plane, 0° at about 23° elevation, and becomes negative at higher elevations (e.g., -3° at about 46°). Conversely, Oldfield and Parker (1984a) observed a small vertical CE ($<\pm 5^\circ$) that did not change with elevation. However, it was slightly affected by the azimuth of the sound source, tending to be negative in front of and positive behind the listener. Best et al. (2009) conducted a meta-analysis of more than 50,000 localization trials using data collected in several laboratories and concluded that elevation errors are (1) biased toward the horizontal plane when the sound source is located in the frontal hemisphere, (2) biased forward and in the lateral direction for sound sources located in the rear hemisphere, and (3) largest for sound sources located overhead and slightly behind the listener. Regardless of direction, the size of the CE is independent of the distance from the sound source and is similar in the proximal and distal regions as long as the source is clearly audible (Brungart, 1999). The size of CE can, however, be greatly influenced by the listener's experience (familiarity with the sound sources) and expectations (Angell and Fite, 1901a; 1901b; Roffler and Butler, 1968a). Both Pratt (1930) and Roffler and Butler (1968a) provided experimental evidence that listeners expect low-pitch sounds to be generated by lower-placed sound sources than high-pitch sounds. According to Pratt (1930) "...prior to any associative addition there exist in every tone an intrinsic spatial character which leads directly to the recognition of differences in height and depth along the pitch-continuum."

Harima et al. (1997) investigated the localization of virtual sound images generated by two separate sound sources located in the median plane. They reported that when the sound sources were located in front of the listener, the sound image was localized at about halfway between the sources as long as the separation angle did not exceed 45° . The sound image was more vague at higher elevations and in the rear of the listener. For a separation angle of 60° , a fused image was hardly possible, and the listeners tended to localize the sound image higher than the midpoint between the two physical sources.

REs in the absolute localization of sound sources in the horizontal and vertical planes in front of the listener are reported to be 4° – 8° and 6° – 8° , respectively (Bronkhorst, 1995; Pedersen and Jorgensen, 2005), although they can be as small as 1° – 3° for sound source discrimination tasks (Blauert, 1974/2001) and as large as 15° in virtual environments (e.g., Bergault and Wenzel, 1993; Majdak et al., 2010). The size of RE increases slightly with sound source laterality but to a lesser degree than the size of CE (Perrott et al., 1987). The poorest precision for localization in the horizontal plane has been reported for angles close to $\pm 150^\circ$ (Tonning, 1970). For a jungle environment, Dobbins and Kindick (1967) reported mean REs in the horizontal plane of 25° ,

20°, and 15° for tones, real-life noises, and impact and impulse sounds, respectively. These values were calculated with the exclusion of all reversal (front-back) errors from the data set (see section 10). When the reversal errors were included in the calculations, the mean errors increased to 39°, 29°, and 23°, respectively. Similar errors (20°–30°) were reported by Eyring (1945) for the localization of rifle shooter positions in a jungle environment. In general, the size of RE in the horizontal plane is smaller than in the median plane for frontal locations, but this pattern is reversed for locations in the rear of the listener (Makous and Middlebrooks, 1990; Carlile et al., 1997). In all the studies cited, intrasubject variability of the data was much smaller than intersubject variability.

Oldfield and Parker (1984a) assessed the ability of listeners to localize sound sources that varied simultaneously in both their horizontal and vertical location. They reported MUE of 9.1° and 8.2° in the horizontal and vertical planes, respectively. The mean horizontal error was largest at $\pm 130^\circ$ – 150° and reached about 15°, while the mean vertical error was relatively independent of azimuth. Similar studies were conducted by Wightman and Kistler (1989b) and Makous and Middlebrooks (1990). While Wightman and Kistler did not report separate horizontal and vertical errors but only the compound error (see section 4), Makous and Middlebrooks reported a range of MUEs from 1.5° in the horizontal plane and 3.5° in the vertical plane for frontal sound source positions (0° position in both the horizontal and vertical plane) to 15–20° at certain combined horizontal/vertical locations. The respective MEs were as small as 0° and –0.3° and as large as –13° and +17° in the horizontal and vertical planes, respectively. Standard deviations (REs) varied from as little as 2.0° to as much as 10.0° in horizontal plane and increased with the degree of laterality. In the vertical plane, they were on the order of 4° at frontal locations and as large as 7°–8° at the extreme positive and negative elevations. The data were screened for front-back errors (see section 10).

The effect of sound reflections and room reverberation on both accuracy and precision of localization judgments is generally detrimental and depends on the space geometry, distribution and strength of the reflections, and the position of the listener within the space (Scharine, 2009; Scharine and Letowski, 2005; Shinn-Cunningham et al., 2005). For example, Rakerd and Hartmann (1985) and Guski (1990) reported that ceiling and wall reflections are more detrimental for auditory localization than floor reflections. For some known sound sources, such as a human voice, floor reflections may even help in improving the accuracy (decreasing CE) of sound source localization (Guski, 1990). With respect to the type of emitted sound, the negative effects of room acoustics are the strongest for narrowband sounds and sounds with very slow rise times, that is, missing an onset time cue (e.g., Giguère and Abel, 1993; Hartmann, 1983a; Rakerd and Hartmann, 1986).

Since in natural environments the sound source is typically facing the intended listener, sound sources are likewise turned toward the listener in almost all localization studies. However, in many practical situations the sound source may well be facing in a different direction. This would have no effect on the listener if the sound source were non-directional, but this is rarely

the case, and no sound sources can be considered non-directional at wavelengths that are much shorter than the dimensions of the sound source (Emanuel and Letowski, 2009). Thus, if a sound source is not facing the listener, the ear closer to the main direction of the sound radiation receives a relatively stronger signal than the other ear. This could create a false IID cue that may result in a noticeable localization CE (Neuhoff et al., 2001; Tønning, 1970). Such errors can be observed, for example, in experiments in which the listener faces a linear horizontal array of loudspeakers that is relatively long or if a moving sound source moves at different oblique angles.

The use of earplugs, earmuffs, or hearing aids also affects localization performance. In general, in-the-ear hearing aids, which minimally obstruct the pinna disturb localization cues to a much lesser degree than all other types of hearing aids (e.g., Leuw and Dreschler, 1987; Westermann and Topholm, 1985). Similarly, earmuffs are more detrimental to localization acuity than earplugs (e.g., Abel and Hay, 1996). Russell and Noble (1976) and Noble et al. (1990) compared localization judgments made with open ears, earplugs, and earmuffs and observed that ear occlusion resulted in rearward CE for the earplug condition and frontward CE for the earmuff condition. The authors concluded that the ear occlusion created false localization cues (CE) rather than increasing the uncertainty of the sound source location (RE). False localization cues can also be produced by dynamic-range compression systems and limiters used in some hearing aids, cochlear implants, and military tactical communication and protection systems (TCAPSs) if they are not synchronized at the two ears (e.g., Byrne and Noble, 1998). Asynchronous compression was determined to affect IID (but not ITD) by several authors, but its effects on localization accuracy were practically negligible (e.g., Mussa-Shufani et al., 2006; Ricketts et al., 2006; Grantham et al., 2008). However, Wiggins and Seeber (2011) reported that fast-acting asynchronous compression at the two ears significantly affects the perceived position of high-pass sounds ($f_c = 2000$ Hz). The perceived locations of sound sources producing sounds with abrupt onset/offset slopes were shifted to more central positions. In contrast, sounds with gradual onset and offset (such as speech) were heard as split or moving images with increased lateral shift of the perceived sound source positions. The severity of these effects can be reduced by the presence of low-frequency ITD cues and completely eliminated by wireless synchronization of both compression systems (e.g., Sockalingam et al., 2009).

Localization accuracy in headphone-based AVRs should be theoretically comparable to the localization accuracy in a free-field as long as an individualized HRTF is accurately measured and reproduced. However, accurate implementation of AVR involves a number of acoustic compromises that have made this goal difficult to achieve (Carlile, 1996), and absolute localization in virtual environments has been typically found to be less accurate than absolute localization in real environments, even if individualized HRTFs are used (e.g., Bronkhorst, 1995; Hartmann and Wittenberg, 1996; Wenzel, 1992). For example, Wenzel and Foster (1993), Middlebrooks (1999ab), and Bergault et al. (2001) reported a CE of 15° – 25° in the horizontal and vertical planes using individualized HRTFs.

With respect to perception of elevation, the perception of elevation in an AVR is far less accurate than in a free sound field with a large number of listeners perceiving the locations of virtual sound sources higher than intended (Folds, 2006). Pedersen and Jorgensen (2005) compared the localization of real and virtual sound sources in the horizontal and median planes and reported REs of 10° and 14° in the horizontal plane and of 12° and 24° in the median plane for real and virtual sources, respectively. Endsley and Rosiles (1995) reported errors reaching 35° in the horizontal plane and 50° in the median plane at large elevations. Bergault and Wenzel (1993) reported average CE of 17° and associated RE of 10° for sound sources in the vertical plane presented at 0° elevations. They also reported an average overall horizontal LE of 28°, while Wightman and Kistler (1989b) reported a similar error of 20° and Endsley and Rosiles (1995) of 35°.

All these data indicate that localization performance in virtual space is greatly dependent on the precision of the HRTF measurement, earphones equalization, the type of signal, listener's movements, and the accuracy of the spatial rendering (e.g., King and Oldfield, 1997). Therefore, localization errors can only be discussed keeping the specific AVR technologies used in the given study in mind.

10. Reversal Localization Errors

10.1 Types of Reversal Errors

Reversal errors are direction estimates of the sound source location that are in the opposite direction to the actual sound source location. They occur when the binaural information correlates equally well with two opposite spatial locations. The listener points not at the sound source but at its mirror image. Such errors can be caused by sound reflections from objects surrounding the listener, the presence of headgear that affects the sound spectrum, listener expectations, or interfering effects of other sounds present in the surrounding environment. Reversal errors are most common for short and narrowband sounds, and the frequency of these errors decreases with increasing sound duration and complexity as the listener is able to use head movements, comprehend the spatial scene, and combine cues across a range of sound frequencies. However, they can happen in any environment and for any sound source under the right circumstances. An example of such a situation was reported by the *Baltimore Sun* (Hermann, 2011). A police officer searching for a suspect in a dark area was accidentally shot in the back by another officer that was following him. The wounded officer thought that the shot had come from in front of him and returned fire in that direction.

In general, reversal errors can be front-back (back-front), left-right (right-left), or up-down (down-up) errors. However, the presence of strong binaural localization cues in humans practically prevents left-right (right-left) reversal errors from occurring (e.g., Bloch, 1893). The

left-right (right-left) judgment errors are only made due to sound source location uncertainty when the sound source is located close to the median plane of the listener or the listener's distraction. Large left-right (right-left) errors are very infrequent and usually constitute less than 1%–2% of overall localization judgements (e.g., Abel and Hay, 1996; Smith-Abouchacra, 1993; Makous and Middlebrooks, 1990).

There is continuing debate in the research literature as to what exactly constitutes a reversal error, and in particular, a front-back (back-front) error. Most authors define front-back errors as any estimates that cross the interaural axis (Carlile et al., 1997; Langendijk et al., 2001; Wenzel, 1999). Other criteria include errors crossing the interaural axis by more than 5° (Jin, 2001), 10° (Schonstein, 2008) or 15° (Best et al., 2009) or errors that are within a certain angle after subtracting 180° . An example of the last case is using a $\pm 10^\circ$ (e.g., Brungart et al., 1999) or $\pm 20^\circ$ (e.g., Carlile et al., 1997) range around the directly opposite angle (position), which corresponds closely to the range of typical listener uncertainty in the frontal direction.

10.2 Front-back and Back-front Errors

Front-back (FB) and back-front (BF) errors are the most common reversal errors, and they happen under all listening conditions but are fairly rare for open ear conditions and relatively absorptive environments (Makous and Middlebrooks, 1990). They are most frequent for sound sources located on or near the median plane, narrowband sounds, and sounds spectrally limited to less than 8 kHz (Nakabayashi, 1974). Typical rates of FB/BF errors reported in auditory localization studies are 2%–12% (Hollander, 1994; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984a; Wenzel et al., 1993; Wightman and Kistler, 1989b). For example, for a wideband sound source at the frontal position, Pedersen and Jorgensen (2005) reported FB/BF error rates of 4.2% and 9.1% for long (2 s) and short (250 ms) stimuli, respectively. For similar, relatively long wideband stimuli, Oldfield and Parker (1984a) and Carlile et al. (1997) reported 3.4% and 3.2% of FB/BF errors, respectively, although in the first study BF errors dominated FB errors and in the second study FB errors dominated BF errors. FB/BF errors are also more common for speech sound sources than for non-speech wideband sound sources (Gilkey and Anderson, 1995).

Usually, FB errors dominate BF errors, but their proportion depends on the visibility of the sound sources, the type of listening environment, and the spectrum of the emitted sound (e.g., Chasin and Chong, 1998). However, in some studies the number of reported BF errors was greater than the number of FB errors (e.g., Abouchacra and Letowski, 2001; Moore, 2009). Abouchacra and Letowski (2001) used speech sounds emitted by an invisible rotating loudspeaker and presented in either non-directional or directional background noise. In both cases, the number of FB/BF errors was dependent on the SNR and was largest when the speech sound source was located at $\pm 135^\circ$.

The number of FB/BF errors usually rapidly decreases with increasing high-frequency energy content in the signal. This is due mostly to the increasing role of monaural spectral cues in

perceiving the sound source location (e.g., Giguère and Abel, 1993). The number of FB/BF errors also decreases with training involving signals with strong monaural cues (Zahorik et al., 2006).

Stevens and Newman (1936) observed that the number of FB confusions among their listeners was much greater for low frequency sound sources (below 2.5 kHz) than for high-frequency sound sources (above 2.5 kHz). Similarly, large numbers of FB/BF confusions for warning siren sounds below 2.5 kHz were reported by Withington (1999). For narrow, one-octave wide noise bands, Burger (1958) reported a 20% rate of FB/BF confusions. For a jungle environment, Dobbins and Kindick (1967) reported 18%, 21%, and 14% FB/BF error rates for pure tones, real-life noises, and impact and impulse sounds, respectively. An exception is the study conducted by Abel and Powlesland (2010), who reported a rate as high as 34% for FB/BF confusions for wideband sound sources located at 15° above or below the interaural line, with 24% being FB errors and 10% being BF errors. According to Kuhn (1987), the effect of the pinna on localization is greatest for azimuths of about 50° and 310°, where the pinna seems to act as a parabolic reflector and greatly differentiates signals coming from the front and back. Therefore, for high frequency sound sources located at these azimuths the number of FB/BF errors should be the smallest.

Virtual environments tend to increase the number of front-back confusions and rates of FB/BF errors vary as much as 12%–20% for individualized HRTFs and 15%–35% for non-individualized HRTFs (e.g., Bergault and Wenzel, 1993; Besing and Koehnke, 1995; Bronkhorst, 1995; Pedersen and Jorgensen, 2005; Ricard and Meirs, 1994; Wenzel et al., 1993; Wightman and Kistler, 1989b). For example, Wightman and Kistler (1989b) reported 5.6% and 11.0% rates of FB errors in a free-field and virtual field (individualized HRTFs), respectively, for the same group of listeners. Similarly, Wenzel et al. (1991) reported 19% and 31% for the same two conditions.

Typical rates of FB errors in virtual environments are in the range of 25%–35% (Bergault and Wenzel, 1993). For 3-D audio presented through earphones, Bergault (1992) reported rates of 27.5% for dry (anechoic-like) and 33% for reverberant synthetic environments. Similarly, Schonstein et al. (2008) reported 37.5%–52% FB error rates depending on the type of earphone and whether the frequency response was equalized or not. Wenzel et al. (1993) reported individual error rates ranging from 20% to 43% (32.0% on average; 25% FB and 6% BF). In another study, Wenzel (1999) reported rates of only 5.2%–8.8% for front-back and 11.3%–21.3% for up-down confusions (including target locations close to the horizontal plane) and 26.2–36.3° overall LEs. However, regardless of listening conditions, FB errors seem to be more numerous than BF errors, and they are most common for horizontal locations close to 0° (Carlile et al., 1997). For example, Bergault and Wenzel (1993) presented speech signals over earphones using non-individualized HRTFs and reported a 58% rate of reversal errors consisting of 47% of FB and 11% of BF errors for 0° and 180° target sounds. The average reversal-corrected CE in the horizontal plane was 24.6° for the 0° direction and 27.9° when averaged across all directions.

This latter error is only slightly larger than the average CE of 20.5° reported by Wightman and Kistler (1989b) for subject SDO listening under similar conditions with her own HRTFs. There are also large individual differences in the case of non-individualized HRTFs. For example, Ricard and Meirs (1994) reported FB error rates of 28.4%, 21.3%, 5.2%, and 45.0% for their four listeners.

When the sound source is located at lateral positions, practically no left-right (right-left) errors are observed, which provides evidence of the strength of binaural cues. Similarly there are very few up-down (down-up) real field errors reported in the literature that are outside the range of uncertainty at the interaural plane, and there is no overall bias toward the upper or lower hemisphere (e.g., Wenzel et al. 1993; Carlile et al., 1997). However, the number of up-down errors in virtual space may be substantial depending on the quality of the simulation. It is noteworthy that when they do occur, most up-down errors, in real or virtual space, are usually associated with simultaneous BF or BF error (Makous and Middlebrooks, 1990; Wenzel et al. 1993).

The importance of knowing the sources of FB/BF errors and using the proper signal design to minimize their occurrence is best seen in studies of human reactions to emergency vehicle sirens. Both Caelli and Porter (1980) and Withington (1999) reported a very high rate of FB errors in response to ambulance sirens. In fact, the study participants were more often wrong than right. These data were collected across several types of emergency sirens including hee-haw, pulsar, wailing, and whooping sounds. Withington (1999) concluded that complex sounds characterized by pulses of rapidly rising frequency sweeps followed by bursts of wideband noises led to improved localization.

10.3 Treatment of Reversal Errors

Some authors (e.g., Cabot, 1977; Gerzon, 1975; Oldfield and Parker, 1984a, Wightman and Kistler, 1989b) eliminate reversal errors by mirroring the perceived reverse locations about the interaural axis prior to data analysis in order to preserve the sample size. Such treatment of reversal errors assumes that each error crossing the interaural axis consists of two components: an actual error and reversal component. Consider a sound source located at 40° and its perceived location at 110° . In this case, the actual error is assumed to be 30° (shift from 40° to 70°) and the reversal component equal to an additional 40° (the difference between 110° and 70°). A rationale offered by other authors is that in real-world environments, where visual cues interact with auditory cues, reversal errors are much less likely to happen and therefore should not be taken into account and eliminated from the data set. This obviously may or may not be true depending on the degree to which the sound source is explicitly visible. However, some reversal errors can be due to listeners' expectations, the presence of baffling headgear, reflections from the environment, the type of sound source (see section 2.5), or simply a shift in the listener's attention. Nevertheless, the mirroring of the reversed estimates may in general decrease the size

of the average localization error in comparison to that obtained by the discarding reversed data points but the actual result depends on the specific distribution of the reversal errors.

The extraction and separate analysis of FB errors should not be confused with the process of trimming the data set to remove outliers, even though both processes may have the same practical effect. Reversal errors are not outliers in the sense that they simply represent extreme errors. They represent a different type of error that has a different underlying cause and, as such, should be treated differently. Any remaining errors that differ more than 2.5 SDs from the mean may be trimmed (discarded) or winsorized to keep the data set within a reasonable range. Winsorizing is a strategy in which the extreme values are not removed from the sample, but rather are replaced with the maximal remaining values on either side. This strategy has the advantage of not reducing the sample size for statistical data analysis. Both these procedures mitigate the effects of extreme values and are a way of making the resultant sample mean and standard deviation more robust.

11. Categorical Localization

Another method of determining LE is to ask listeners to specify the sound source location by selecting from a set of specifically labeled locations. These locations can be indicated by either visible sound sources or special markers on the curtain covering the sound sources (Abel and Banerjee, 1996; Butler et al., 1990; Giguère and Abel, 1993; Hammershoi and Sandvad, 1994; Hawley et al., 1999). Such approaches restrict the number of possible directions to the predetermined target locations and lead to categorical localization judgments²³ (Perrett and Noble, 1995). The results of categorical localization studies are normally expressed as percents of correct responses rather than angular deviations. For example Bienvenue and Siegenthaler (1974) compared the binaural and monaural abilities of listeners to distinguish between seven loudspeakers distributed around them as the source of a projected speech signal and reported 97% and 52% correct response rates, respectively. Abel et al. (2007) used eight loudspeakers unevenly distributed on a circle (two loudspeakers in each spatial quadrant) in comparing various types of ear occlusions and reported 94% and 49% correct response rates for open ears and ears covered with passive earmuffs (Peltor H10A), respectively.

Although categorical localization was the predominant localization methodology in older studies (e.g., Bergman, 1957; Bienvenue and Siegenthaler, 1974; Kuyper and de Boer, 1969), it is still commonly used today (Abel and Banerjee, 1996; Inoue, 2001; Macaulay et al., 2010; Van Hoesel and Clark, 1999; Vause and Grantham, 1999). For example, the Source Azimuth Identification in Noise Test (SAINT) uses categorical judgments with a circular array of 12 loudspeakers (Vermiglio et al., 1998) and a standard system for testing the localization ability of

²³Hartmann et al. (1998) call categorical localization judgments “source-identification method” judgments.

cochlear implant users is categorical with 8 loudspeakers distributed in a symmetric manner in the horizontal plane in front of the listener with 15.5° of separation (Tyler and Witt, 2004).

The main attractiveness of categorical localization studies lies in the fact that they are easy to instrument and run. In many industrial and clinical settings the equipment that would allow testing via a non-categorical paradigm may be even not available. However, in such testing paradigm, the angular distance between the labeled target locations may be de facto the resolution of the localization judgments and may define the localization precision of the study. With a small number of sound sources, the resolution is very poor, and with a large number of sound sources, the numerous labels may confuse the listener since they could be hard to associate with specific directions. Based on the analysis of loudspeakers arrays conducted by Hartmann et al. (1998) it can be conjectured that the minimum number of sound sources in a loudspeaker array spanning no more than 180° should be somewhat larger than 7–9. Further increase in the number of loudspeakers within a given arc does not affect much the size of localization error. If the array exceeds 180°, the specific (asymmetrical) locations of the loudspeakers in the front and back are more important than the actual number of loudspeakers in order to resolve FB and BF confusions. Due to these limitations, a categorical localization paradigm is generally suitable for sound sources and headgear evaluation studies, and should not be in general used in research investigating human abilities.

In order to directly compare the results of a categorical localization study to an absolute localization study, it is necessary to extract a mean direction and standard deviation from the distribution of responses over the target locations. If the full distribution is known, then by treating each response as an indication of the actual angular positions of the selected target location, the mean and standard deviation can be calculated as usual. If only the percent of correct responses is provided, then as long as the percent correct is over 50%, a normal distribution z-table (giving probabilities of a result being less than a given z-score) can be used to estimate the standard deviation. If d is the angle of target separation (i.e., the angle between two adjacent loudspeakers), p is the percent correct, and z is the z-score corresponding to $(p+1)/2$, then the standard deviation is given by

$$\sigma = \frac{d}{2z} \quad (45)$$

and the mean by the angular position of the correct target location. This is based on the assumption that the correct responses are normally distributed over the range delimited by the points half way between the correct loudspeaker and the two loudspeakers on either side. This range spans the angle of target separation (d) and thus $d/2$ is the corresponding z-score for the actual distribution. The relationship between the standard z-score and the z-score for a normal distribution $N(\mu, \sigma)$ is given by:

$$z_{N(\mu, \sigma)} = \mu + \sigma \cdot z \quad (46)$$

In this case, the mean, μ , is 0 as the responses are centered on the correct loudspeaker position, so solving for the standard deviation gives equation 45. As an example, consider an array of loudspeakers separated by 15° and an 85% correct response rate for some individual speaker. The z-score for $(1 + 0.85)/2 = 0.925$ is 1.44, so the standard deviation is estimated to be $7.5^\circ/1.44 = 5.2^\circ$.

An underlying assumption in the preceding discussion is that the experimental conditions in the categorical task are such that the listener is surrounded by evenly spaced target locations. If this is not the case, then the results for the extreme locations at either end may have been affected by the fact that there are no further locations. In particular this is a problem when the location with the highest percent of responses is not the correct location and the distribution is not symmetric around it. For example, this appears to be the case for the speakers located at $\pm 90^\circ$ in the 30° loudspeaker arrangement used by Abel and Banerjee (1996).

Categorical judgments are also used in some vertical localization studies. Davis and Stephens (1974) argued that at very low intensity levels vertical localization becomes very difficult and it is much easier for the listeners to make their judgments when a range of possible locations is provided to them.

12. Directional Audiometry

Human localization ability has received a great deal of attention from the research community over the last 100 years, but there have only been limited efforts to develop audiological tests of this ability, as it was not clear what value directional hearing tests would provide for clinical diagnostics. Sound source localization is an important task repeated many times each day, but the large variability of localization data, even for people with the same type of hearing or type of hearing loss etiology (e.g., Abel et al., 1978; Bocca et al., 1955; Nordlund, 1964; Wilmington et al, 1994), as well as technical problems with creating spatially uniform testing conditions, hampered progress in developing standardized directional hearing tests. In addition, the obvious causes of localization performance degradation related to the mechanics of the outer and middle ears (e.g., atresia, otitis media, otosclerosis) can be determined without localization tests, so there was no need for spatial audiometric tests for these purposes. Accordingly, only limited sound field tests have been developed for testing children and hearing aid evaluation using a single loudspeaker located either close to the listener's ears (<25 cm) or about 1 m away at 0° , 45° and/or 90° angles (e.g., ASHA, 1991; Goldberg, 1979; 1981; Walker et al., 1984). In some cases two loudspeakers were used.

Consistent reports by people who are hard of hearing, as well as by some normal hearing listeners, of difficulties in localizing sound sources outside their field of view and comprehending speech coming from behind contributed in the end to efforts to develop

directional hearing tests for clinical practice. The clinical importance of LE was also supported by the growing diagnostic value of sound lateralization tests conducted under earphones (e.g., Almqvist et al., 1989; Furst et al., 2000). Equally importantly, auditory localization tests also became useful for testing the directional properties of hearing aids, especially those with directional microphones, assistive technology, and, more recently, for testing the directional hearing restoration of cochlear implants users.

Directional hearing tests to assess hearing deficiencies, commonly referred to in the medical community as *directional audiometry* or *spatial audiometry*, seem to have originated from the work of Goodhill (1954), Hahlbrock et al. (1959), Jongkees and Groen (1946), Jongkees and Veer (1957), and Sanchez-Longo et al. (1957). In the early 1970s, Tonning published a series of eight papers (Tonning, 1970, 1971ab, 1972abc, 1973ab) on the development and use of directional hearing tests for audiological applications. It is noteworthy that six of Tonning's papers are related to directional speech intelligibility (DSI) testing and only two of them (Tonning, 1970; 1973b) address localization issues. Other publications proposing some forms of directional audiometry included Nordlund (1962ab, 1964), Link and Lehnhardt (1966), Bienvenue and Siegenthaler (1974), Cook and Frank, 1977; Newton and Hickson (1981), Zera et al. (1982), Noble et al., (1994), and Besing et al. (1999b). In all these cases directional audiometry was limited to sound source localization in the horizontal plane. Over the years, three basic forms of directional audiometry testing have emerged:

1. The listener is surrounded by loudspeakers, and the loudspeakers and listener both remain stationary (Abouchacra et al., 1998a; Bienvenue and Siegenthaler, 1974; Cook and Frank, 1977).
2. The listener is surrounded by loudspeakers but rotates their chair toward the incoming sound (Hahlbrock et al. 1959; Link and Lehnhardt, 1966).
3. A single loudspeaker rotates (or can be rotated) around a stationary listener (Elfner and Howse, 1987; Newton and Hickson, 1981b; Nordlund, 1964; Sanchez-Longo et al. 1957; Zabrewski, 1960).

Some examples of the technical arrangements used in all three forms of directional audiometry testing are listed in table 3.

Table 3. Some examples of the technical arrangements used in directional audiometry tests.

Author	Test Form	Signal	Level (dB SPL)	Comments
Sanchez-Longo et al. (1957)	(c)	60-Hz tone with harmonics	90 dB HL	13 positions separated by 15° ($\pm 90^\circ$ range); single loudspeaker hidden behind semicircular screen and moved by hand; T<10 s.
Link and Lehnhardt (1966)	(b)	white noise		13 fixed loudspeakers separated by 10° ($\pm 60^\circ$ range); response interval: 1.7° using a <i>directional table</i> ; signal duration: short impulse
Hattori (1966)	(a)	narrow band noise (1 kHz)		3 fixed loudspeakers (0°, $\pm 90^\circ$); phantom sound sources at $\pm 5^\circ$, 10°, 15°, 20°, 25°, 40°, 50°, 60°, and 70°
Tonning (1970)	(c)	white noise	65 dB SPL	2 rotating loudspeakers; signal duration 10 s; response markers: 2.5°
Bienvenue and Siegenthaler (1974)	(a)	speech phrase “where is this”	15 dB SL	7 fixed loudspeaker mounted on the ceiling and separated by 45° (no front loudspeaker); response: loudspeaker number
Humes et al. (1980)	(a)	0.5- and 3.0-kHz pure tones	60 dB SPL	13 loudspeakers separated by 15° ($\pm 90^\circ$ range); response: loudspeaker number
Newton and Hickson (1981)	(c)	0.5-kHz tone and narrow band noise (500 Hz)		random angle in the 64° to 117° range; signal duration 5 s; response: spoken angular estimate
Vermiglio et al., 1998 (SAINT test)	(a)	various natural sounds	55 dB A	12 loudspeakers unequally distributed over 360°; 1 overhead loudspeaker for masker presentation (SNR = -5 dB)
Besing et al. (1999b)	(a)	speech phrases	50 or 70 dB SPL	2 loudspeakers; 9 spatialized phantom locations separated by 10° ($\pm 40^\circ$ range);
Besing et al. (1999b)	(a)	speech phrases	50 or 70 dB SPL	8 loudspeakers separated by 20° ($\pm 70^\circ$ range); no front loudspeaker

Despite the several proposed testing configuration and data collection procedures, the clinical community has not yet agreed on a single standard clinical procedure for evaluating directional hearing. The unresolved issues include the technical requirements for the test system, comprehensive yet flexible test procedures, and most importantly, normative data for directional hearing. However, there is some progress toward standardization. For example, there seems to be a consensus that the two best directional audiometry signals are low-pass (up to 0.5–1.0 kHz) and high-pass (above 2–4 kHz) white noise signals that can separately test temporal and intensity-based elements of spatial hearing. Another possibility is to use octave-wide bands of noise. A method of delivering directional signals by rotating loudspeaker has gained some popularity (e.g., Abel et al., 1982; Comalli and Altshuler, 1980). As a clinical criterion of normal localization ability (horizontal plane; frontal location), the localization accuracy of 10° has been suggested (e.g., Comalli and Altshuler, 1980).

The main question for directional audiometry, however, remains: How can localization data be linked to specific health issues? This was originally a question without a clear answer, and the view that the relationship between hearing loss and auditory directional sensitivity was only moderate was commonly held (e.g., Noble et al., 1994). However, by including listeners with a variety of hearing disorders in localization studies, the research community is learning more and

more about the potential links between localization ability and specific hearing disorders. The first study of this kind seems to have been carried out by Greene (1929), who suggested that lesions in the temporal lobe may be related to poor directional hearing. Similar conclusions were reached by Sanchez-Longo et al. (1957) and Jerger et al. (1969). Degraded directional hearing has also been reported in cases of otosclerosis (Jongkees and Veer, 1957; Newton and Hickson, 1981; Nordlund 1962ab, 1964) and acoustic neuroma (Abel et al., 1982; Liden and Korsan-Bengsten, 1973; Newton and Hickson, 1981). There is also growing evidence that directional audiometry can help differentiate between most cochlear and some cortical lesions, and lesions in the middle ear, cochlear nerve, and retrocochlear (points) region. The former cause no directional hearing deficit, whereas the latter result in impaired directional hearing (e.g., Nordlund, 1964; Azzi, 1964). Further, changes in listeners' localization patterns may help to differentiate brain lesions at the SOC and IC levels (e.g., Aharonson and Furst, 2001) (see section 4). However, it is still unclear to what degree lesions of the vestibular system affect directional hearing (Diamant, 1946; Jongkees and Veer, 1958; Nordlund, 1964; Tonning, 1975). Since the listener remains stationary during sound presentation in directional audiometry, it is very unlikely, as Blauert (1974/2001) points out, that such testing can reveal any disorder of the vestibular system. There are, however, some reports indicating that very strong sounds and head vibrations may elicit a response from the vestibular system even if the person remains stationary (Parker et al. 1968; Parker and Gierke, 1971). A review of older literature on the effects of hearing disorders on directional hearing may be found in Durlach et al. (1981).

Both the research and clinical communities are aware that some of the differences in the reported effects of lesion site on patients' auditory localization ability may be due to superficial differences in the acoustics of the spaces used in directional audiometry and the lack of consistency and clarity regarding the test criteria. For example, in the sound field studies geared toward the development of directional audiometry tests, a head restraint should be used in order to minimize potential contributions of dynamic cues that can confound the findings (see section 2.3). This has not always been the case in the reported studies. Similarly, some authors reported LE, while others reported CE or RE, and in many cases, the type of error reported by the authors was not clear. However, the type of LE made by a listener is very important in clinical evaluation. According to Nordlund (1962ab, 1964), Newton and Hickson (1981), and Abel et al. (1982), abnormality in RE, that is, a greater than normal inconsistency of localization responses, constitutes diagnostic evidence of hearing problems, especially of sensorineural hearing loss. These authors also argued that CE toward either direction has little diagnostic value in determining the potential site of a lesion. In contrast, according to Abel et al. (1982), persons with neuroma tend to make CEs by shifting the perceived image toward the unimpaired ear. Such persons may also have problems distinguishing sound source positions on either side of the median plane (Abel et al., 1982).

There have only been a few attempts to extend directional audiometry to vertical localization. The first reported attempt was most likely made by Walsh (1957), who reported that in a number

of brainstem and cerebral lesion cases, horizontal localization ability remained intact while vertical localization accuracy (CE) was noticeably affected. Interest in clinical testing of vertical localization may increase with the development of virtual directional audiometry, which would allow easy presentation of phantom sound sources from any angle in 3-D space (e.g., Bergault, 1992; Besing et al., 1999b). Such audiometry is based on synthetic out-of-the-head spatial audio environments (AVR environments) presented through earphones (e.g., Abouchacra et al., 1998b; Besing and Koehnke, 1995; Besing et al., 1999a; Koehnke and Besing, 1996; 1997ab; Vermiglio et al., 1998). The tests proposed by various authors include DDT tests, localization accuracy tests, and speech-in-noise (cocktail party effect) tests. Speech-in-noise tests include both directional and ambient noise maskers (e.g., Abouchacra and Letowski, 2004; 2005; Abouchacra et al., 2009). Both the tests for adult and children populations have been proposed (e.g., Besing et al., 1998). Some common elements of the virtual directional audiometry tests proposed to date include the use of speech test signals and out-of-the-head phantom sound source locations separated by 22.5° . Note that previous attempts to use earphones without virtual out-of-the-head spatialization failed due to in-the-head localization, which is both unnatural and inaccurate in resolving phantom sound source locations (e.g., Nordlund, 1962b). Further improvements in the standardization of directional audiometry may result from the standardization efforts of the American National Standards Institute (ANSI), which established two working groups, S3/WG83 and S3/WG89, to evaluate the feasibility of natural and virtual directional audiometry, and develop unified procedures for directional hearing tests in both real and virtual spaces.

In the only study of its kind to date, Vermiglio et al. (1998) compared real sound field (loudspeakers; eight sources) and virtual sound field (earphones; six sources) versions of their SAINT test (see table 3) and concluded that although the headphone test was less sensitive than the loudspeaker test (with the difference attributed to the fewer number of sound sources), both tests demonstrated similar test-retest reliability. This is an important finding since regardless of the advances of virtual earphone-based directional audiometry, free-field audiometry will always be required for testing the effects of hearing aids, hearing protectors, and other headgear on people's ability to identify the direction of incoming sounds.

13. Localization of Multiple Sound Sources

Most auditory localization studies to date have focused on the localization of a single sound source either in isolation or with a more or less complex acoustic background environment (see section 9). However, our daily listening situations are much more complex than those and can require that we pay attention to more than one sound source at a time. For example, a blind person walking in the street must pay attention to several sound sources in order to walk safely and effectively. While selective attention tasks where the listener focuses on a specific sound source are well researched in the psychoacoustic literature, divided attention tasks are not often

addressed, and very few studies to date considered situations in which a listener had to identify and/or localize two or more simultaneously active sound sources.

The simultaneous localization of two or more sound sources located at different positions in space is very demanding task, especially if there is complete or even partial overlap between the spectral and temporal patterns of the emitted sounds. When sounds produced by two or more sound sources have similar sound onset and harmonic structure, they may be fused into one event with a single real or virtual source of origin. This fusion effect results from the rules of *auditory scene analysis* (ASA) performed by the listener's central auditory system (Bregman, 1990; Shinn-Cunningham and Durlach, 1994; Woods and Colburn, 1992). One common example of such a fusion effect is the *precedence effect* (see section 2.4). In general, if two or more sound sources are synchronously presenting similar (e.g., harmonically related) sounds from different locations in space, their timing serves as a grouping cue and only the location of the lowest frequency sound is perceived if all sounds arrive at the same time (Best et al., 2007). Therefore, to facilitate localization of two or more simultaneously active sound sources located at the same distance from the listener, the sources have to be both well-separated in the space and emit sounds that are easy to distinguish by the listener (Bregman, 1990).

The first attempt to measure a threshold for distinguishing between the locations of two concurrently active sound sources was reported by Perrott (1984a), who referred to this threshold as the concurrent minimum audible angle (CMAA). Perrott presented two simultaneous tones of differed pitch from two sound sources located in the horizontal plane and asked listeners to report if the higher tone was located to the left or to the right of the lower tone (Perrott, 1984a). The CMAA values reported for a 75% correct identification rate varied from 5°–10° at the frontal location to as much as 30°–45° for a lateral azimuth of 67°. Similar data were reported by Divenyi and Oliver (1989) for amplitude- and frequency-modulated tones and Best et al. (2004) for broadband sounds. Results of all these studies indicate that pitch similarity and spectral overlap decrease the resolution of concurrent sounds and increase the CMAA value.

Hollander (1994) measured the CMAA at the frontal direction using harmonic complexes that differed in their fundamental frequency (1000 and 1050 Hz) and reported much poorer spatial resolution than Perrott (1984ab) and Divenyi and Oliver (1989). He also observed large intersubject variability in the results. Among the seven listeners in the study, horizontal and vertical CMAAs varied from 20° to 60° and 20° to 80°, respectively. Best et al. (2003) modified the CMAA paradigm by presenting two identical broadband sounds from two loudspeakers and asking listeners whether they heard the sound as coming from a single location or from two distinct locations either in azimuth or elevation. The spatial resolution data in the horizontal plane were poorer but qualitatively similar to those obtained by Perrott (1984ab) and Divenyi and Oliver (1989). The source separation needed to spatially resolve two sources was location-dependent and varied from 21° in front of the listener to about 45° at a 90° lateral angle. For two concurrent sound sources located at different elevations, listeners were practically unable to

separate them in the median plane but could discriminate between them at lateral angles, e.g., at the frontal plane, when the angular separation exceeded 50°–60°.

The first experiment (that we are aware of) involving the simultaneous localization of several well-separated sound sources was reported by Rowell and Kay (1968), who presented blindfolded listeners with five different sound sources (loudspeakers) emitting the same signal and asked them to identify the number and location of the sound sources. Obviously, this was an impossible task as (in effect) the listeners only heard one sound coming from a single location that changed as they moved in the space. The purpose of this experiment was to prove that multiple simultaneously active sound sources must have very different characteristics to be heard separately.

Parmentier and Jones (2000) conducted a study in which listeners were asked to remember and recall a sequence of sounds presented in random order by nine loudspeakers placed at 40° intervals around the listener. The authors reported the presence of primacy and recency effects, resulting in a large number of errors in which listeners erroneously selected the loudspeaker that had emitted the preceding sound instead of the loudspeaker emitting the current sound. In contrast, very few spatial errors, that is, the selection of an adjacent loudspeaker instead of the correct one, were reported. In a similar study, Klatzky et al. (2002) presented three or five words in sequence from three or five loudspeakers placed at least 30° apart. Each word was presented through a specific loudspeaker, and the listeners' task was to associate specific words with specific sound sources. The authors reported that the listeners learned the task more quickly for three than five spatially separated word/loudspeaker combinations.

The first study in which listeners were actually asked to simultaneously localize multiple sources concurrently presenting different sounds was done by Brungart et al. (2005). Listeners were asked to localize the sources of up to 14 different broadband continuous noises. The individual sources were turned on in sequence, and each time a new source was added the listener was asked to identify its location. Localization accuracy declined steadily with increasing number of active sound sources but remained higher than chance even when all 14 sound sources had been turned on. Head movements were found to be helpful in the localization task for up to five active sound sources but not beyond that level.

A group of concurrent sound sources was also used in the studies by Simpson et al. (2007) and Santala and Pulkki (2011). Simpson et al. presented n concurrent non-speech sounds and then eliminated one of the sources and asked the listeners to indicate where the eliminated sound source had been located. The LE was on the order of 5° for $n = 2$, 10° for $n = 4$, 25° for $n = 6$, and 35° for $n = 8$ (for the sounds and conditions used in the study). Santala and Pulkki presented uncorrelated pink noise bursts through groups of 1 to 13 loudspeakers (1, 2, 3, 4, 5, 7, 11, 13) distributed in the frontal horizontal plane and asked their listeners to identify all the loudspeakers emitting the sound at the given time. The general conclusion that emerged from the study was that the listeners were unable to identify the spatial details of the sound field when there were

more than three loudspeakers emitting sound concurrently. Note that in this study, the listeners' task involved focusing on all sound sources simultaneously rather than on one of them at a time as in the Brungart et al. (2005) and Simpson et al. (2007) studies.

Martin et al. (2011) presented listeners with up to six sources of environmental sounds positioned around the listener in an AVR space. The sequence of 1 to 6 sounds was presented 1, 3, or 5 times, and the target sound was revealed after the presentation of the last sequence. The listener's task was to identify the location of the sound source that produced this sound. As in the previous studies mentioned, pronounced primacy and recency effect were found. Further research in this area is needed to determine the human ability to localize two or more sound sources that simultaneously (or within a short time frame) produce sounds of short duration and to determine the limitations of spatial auditory attention in construing auditory awareness of the surrounding environment.

14. Perception of Moving Sound Sources

Our ability to perceive motion is very important in our ongoing interactions with the surrounding world and is the key to our ability to detect and avoid threats. Both the visual and auditory senses can detect and monitor the motion of objects moving along various trajectories if their motion is relatively slow (Stern et al., 2006). A person can discriminate direction of motion, estimate distance travelled, and assess velocity of the tracked object. In addition, tracked objects can rotate (turn to the left or right), tilt (pivot) toward one side or the other, and/or tumble (turn up or down), that is, make changes in their relative yaw, roll, and pitch, each of which can affect both senses of motion perception.

The two main cues that enable a listener to track the direction of a moving sound source are angular velocity and radial velocity cues. Other variables affecting perception of movement include distance from the listener, Doppler frequency shift, sound intensity, and interaural differences (e.g., Ericson, 2000; Rosenblum et al., 1987). Angular velocity is the velocity at which the sound source rotates around the listener, while radial velocity is the velocity at which it moves toward or away from the listener. Movement of the sound source toward (or away from) the listener causes changes in the sound intensity perceived by the listener and produces a frequency shift in the perceived spectrum of the moving sound due to the Doppler effect. Sound waveforms produced by a sound source moving toward the listener become compressed along the axis of movement, which results in a higher effective sound frequency. When a sound source moves away from the listener, the effect is reversed, and the effective sound frequency is lower. Mathematically, the effect is expressed as follows:

$$f_o = f_s \frac{c + v_o}{c - v_s}, \quad (47)$$

where f_o is the frequency of the sound as heard by the listener, f_s the frequency of the sound produced by the sound source, c the velocity of sound in the medium, v_s the velocity of the sound source relative to the medium, and v_o the velocity of the observer relative to the medium. The convention regarding positive (+) and negative (–) directions of movement as used in equation 47 is shown in figure 16.

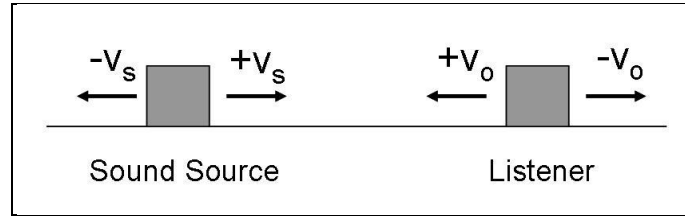


Figure 16. Positive (+) and negative (–) directions of movement used in the formula.

The Doppler effect causes a semitone shift in sound spectrum for each change of 42 mph (67.6 km/h) in relative velocity. When a sound source travels along a trajectory that does not intersect the listener's location, the radial velocity (v_{obs}) of the source varies as a function of the angle, α , between the direction of the source's velocity (v_{source}) and the line connecting the source with the listener as

$$v_{obs} = v_{source} \cos \alpha \quad (48)$$

Note, however, that some authors (e.g., Laroche, 1994) erroneously state that the Doppler frequency *increases* as the source, moving at constant speed, approaches an observer and then *decreases* as it passes the observer. In reality, as the sound source approaches the listener, the Doppler frequency is higher than the emitted frequency but does not change until the sound source passed the listener at which point it drops to a value below the emitted frequency and again does not change as it moves away from the listener. Bohren (1991) argued that the perception of increasing frequency for the approaching sound source is the effect of increasing sound intensity as the sound source nears the listener, which is misinterpreted as an increase in signal frequency.

Although changes in distance may be cued by sound intensity differences or by the Doppler shift in sound frequency, changes in vertical and horizontal angle are cued by binaural and monaural localization cues. The primary metric used in reporting perceived sound source motion is the minimum audible movement angle (MAMA). The MAMA is defined as the smallest angular distance the sound source has to travel so that its direction of motion is detected. In other words, the MAMA is the detection threshold for movement, whereas the MAA is the detection threshold for location. The MAMA is usually larger than the MAA, typically twice as large, for the same sound source and the same initial (reference) direction and is independent of direction of movement in the horizontal plane (e.g., Chandler and Grantham, 1992; Grantham et al., 2003; Perrott and Musicant, 1977) and signal intensity (Perrott and Marlborough, 1989). Similarly to

the MAA, the MAMA is smallest in front of the listener and increases as the sound source moves away from the listener laterally (Harris and Sergeant, 1971; Grantham, 1986); is smaller for wide- than narrow-band stimuli (Harris and Sergeant, 1971; Saberi and Perrott, 1990); and is largest in the mid-high frequency range (Perrott and Tucker, 1988). In general, MAMAs are U-shaped functions of velocity, with optimum resolution obtained at about 8° – 16° /s in the horizontal plane and 7° – 10° /s in the vertical plane (Saberi and Perrott, 1990).

At low horizontal angular velocities (below 20° /s), the MAMA at the midline (0°) is relatively small (on the order of 2° – 8° ; Perrott and Marlborough [1989] reported 1°) but becomes larger (10° – 20°) as velocity increases (Carlile and Best, 2002; Chandler and Grantham, 1992; Harris and Sergeant, 1971; Perrott, 1982; Perrott et al., 1993; Saberi and Perrott, 1990). Grantham (1997) reported MAMAs of 4.8° and 7.8° at velocities of 20° /s and 60° /s, respectively. A MAMA of 20° was also reported for a velocity of 180° /s by Chandler and Grantham (1992) and for a velocity of 360° /s by Grantham (1986) and Perrott and Musicant (1977). Strybel et al. (1992b) reported that at a velocity of 20° /s, the initial position of the sound source did not significantly affect the MAMA for azimuth locations in the $\pm 40^{\circ}$ range. Within this range, and at elevations below 80° , the MAMAs were surprisingly small (1° – 2°) but increased to 3° – 10° outside of this range. However, Chandler and Grantham (1992) reported MAMAs being 1.5 to 3.0 times larger at a 60° azimuth than at the midline (0°). Some variability in the reported data may be caused by the degree of spatial adaptation to the initial position of the subsequently moving sound source available to the listener (Getzman and Lewald, 2011).

For sound source velocities exceeding 10° /s, the horizontal MAMA is linearly related to the sound source velocity (Chandler and Grantham, 1992; Perrott and Musicant, 1977). This means that a certain minimum amount of sound source movement in this velocity range is required for the listener to detect and process changes in sound source location (Scharine et al., 2009). In other words, the MAMA is a displacement threshold, that is, the minimum noticeable displacement of a sound source moving at a constant velocity. Note that the MAMA is a product of sound source velocity and the duration of movement (stimulus duration). According to Chandler and Grantham (1992), this minimum noticeable angular displacement corresponds to a period of observation (minimum duration) varying from about 300 ms (target at midline) to about 1200 ms (target at 60°), except for very high sound source velocities (above about 100° /s). Altman and Andreeva (2004) reported a minimum duration of 150–200 ms in the 0° – 60° range of observation angles and $\sim 25\%$ – 30% longer durations at larger angles for sound sources moving at low velocities. The general relationship between the MAMA, sound source velocity, and duration of movement is shown in figure 17.

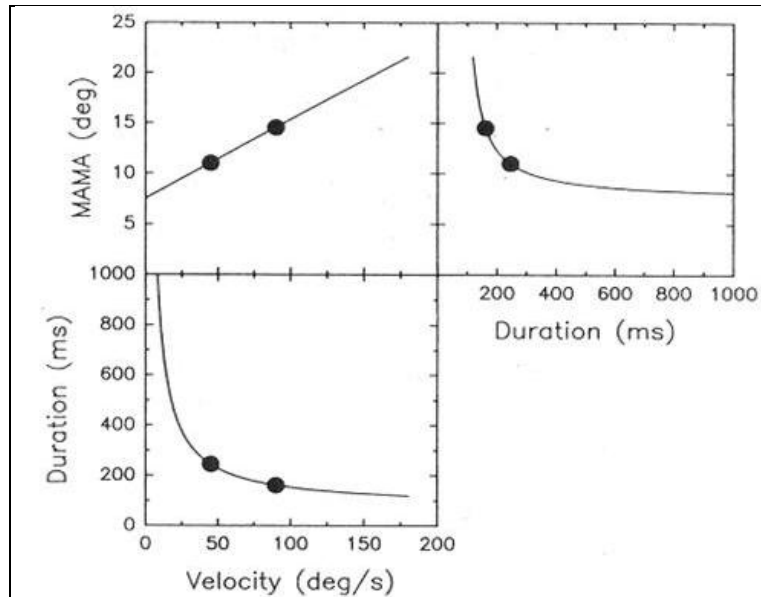


Figure 17. Relationship between the MAMA, sound source velocity, and duration of movement (stimulus duration). Adapted from Chandler and Grantham (1992).

Another perceptual characteristic of moving sound sources is the velocity threshold (Grantham, 1983). The velocity threshold is the minimum source velocity needed to detect sound source movement in a given constant period of observation. This velocity depends on the duration of the observation period (T) and the sound spectrum/frequency (f). Grantham (1983) observed that for $T = 500$ ms, the velocity threshold was $10^\circ\text{--}15^\circ/\text{s}$ and about $40^\circ/\text{s}$ for sound sources producing a pure tone of $f = 250, 500$, or 1000 Hz and $f = 2000$ Hz, respectively. Carlile and Best (2002) have sound sources moving at $15^\circ/\text{s}$, $30^\circ/\text{s}$, and $60^\circ/\text{s}$ velocities with no displacement cue (constant displacement) and reported velocity thresholds of 5.5° , 9.1° , and 14.8° , respectively.

When a displacement cue was included, the velocity thresholds dropped to about half of their previous values. The velocity DL²⁴ is nearly linearly related to the velocity of the sound source. Altman and Viskov (1977) reported a velocity DL increasing from $10.8^\circ/\text{s}$ to $19.3^\circ/\text{s}$ for sound source velocity increasing from $14^\circ/\text{s}$ to $140^\circ/\text{s}$. The listeners tend to underestimate the velocity of sound source motion for short observation periods (30–100 ms) but they are quite accurate for sounds of longer durations (Perrott et al., 1979).

Using continuously varying ITDs and IIDs, Blauert (1972) and Grantham and Wightman (1978) found that the maximum rate at which movement around a listener could be continuously followed by the listener is less than 2–3 Hz ($720^\circ\text{--}1080^\circ/\text{s}$). At rates of 3–6 Hz, the listener begins to hear a sound oscillating between the left and right ear (Aschoff, 1962; Blauert, 1972)

²⁴ DL is the differential threshold and is also called just noticeable difference (JND).

and above about 10–20 Hz, no rotational movement is perceived at all—just a constant blur (e.g., Aschoff, 1962; Grantham and Wightman, 1979).

In the memory-recall studies of moving sound sources, the initial position of a moving target is usually displaced in the listener's memory in the direction of the target's motion and this shift needs to be taken into account in bridging the gap between perception and action (Hubbard, 2006). This shift is sometimes called *representational momentum* and/or the *Fröhlich effect* (Fröhlich, 1923; Getzmann, 2005). Displacement of the localized initial position of the moving sound source is largest with the peripheral initial positions and decreases as the initial position moves closer to the median plane (Getzmann, 2005). This observation supports the notion that spatial auditory memory is orientation dependent (e.g., Yamamoto and Shelton, 2009). In the case of a moving continuous noise source, the size of the Fröhlich effect depends on the velocity (8°/s vs. 16°/s) of the moving sound source (larger LE for slow velocities), although the effect of velocity seems to disappear for pulsed noise sources (Getzmann, Lewald, and Guski, 2004).

In most studies of the moving sound sources, the sound source moves along a circular path around the listener. For this type of sound source movement, the sound frequency/spectrum, and the sound intensity at the listener's location are independent of sound source position, and the MAMA is primarily dependent on binaural cues (e.g., Dong et al., 2000). For linearly moving sound sources, the movement of the source passing the listener produces a change in frequency and changes in sound pressure level due to the changing distance between the sound source and the listener (Lee and Wang, 2009; Lufti and Wang, 1994; Rosenblum et al., 1987). Lufti and Wang (1999) and Kaczmarek (2005) reported that the velocity DL for a sound source moving along a linear trajectory is relatively independent of both the initial velocity (10–50 m/s range) and the initial position of the sound source in space. At low initial velocities of about 10 m/s, changes in the position of a sound source moving at constant velocity are determined on the basis of interaural differences (IIDs and ITDs), and changes in its velocity are determined on the basis of the Doppler effect. At high velocities (about 50 m/s), the Doppler effect is the main cue for all discrimination tasks (Lufti and Wang, 1999). However, the average velocity DL varies broadly across listeners, e.g., from 1.5 to 4.6 m/s (Kaczmarek, 2005). The results of all these studies suggest that a listener's perception of the motion of a moving sound source depends more on the changes in sound frequency and intensity than on binaural localization cues.

The MAMA in the median plane was initially measured by Saberi and Perrott (1990) at the 0° elevation. They found that it is a U-shaped function of velocity with a minimum at 7°–11°/s. Under these optimal velocity conditions, the MAMA is about 6°. Differential thresholds (DLs) in median plane were measured by Agaeva (2004) at vertical velocities of 58°/s and 115°/s. She reported that the DL values were dependent on the type of movement (stepped vs. continuous), the sound spectrum (higher DLs for low frequency noises), and the sound source velocity (larger DLs for 115°/s).

Saberi and Perrott (1990) studied the MAMA for sound sources moving in diagonal and oblique planes. Similarly to the MAA measured in the same planes, the MAMA for the 45° plane was practically the same as for the 0° plane. Furthermore, the MAMAs measured for the 80° and 87° planes were still substantially smaller than the MAMAs measured for the median (90°) plane.

There are two theories of motion perception: the *snapshot theory*, according to which the listener compares the initial and final angles of a sound source's position to evaluate its potential motion, and the *continuous motion theory*, according to which a listener actually monitors the motion of the sound source (Perrott and Marlborough, 1989). An argument for the snapshot theory is that a sound source does not need to actually move to create the sensation of movement. The proper timing of two acoustic stimuli produced from two separate sound sources can produce the sensation of sound source motion called *auditory apparent motion* (AAM) (Strybel et al., 1998). Stimulus timing is determined from the durations of both stimuli and the difference in their onset times, called stimulus onset asynchrony (SOA). The spatial separation between the two sound sources does not affect the strength of the AAM sensation and only affects the perceived velocity of motion (Perrott and Strybel, 1977; Strybel et al., 1998). For example, Strybel et al. (1990) reported that two sound bursts with durations of 50 ms and a SOA of 40–60 ms can produce an AAM with sound sources separated by as little as 6° or as much as 160°. Similarly, Bremer et al. (1977), Hari (1995), and Shore et al. (1998) observed that a click train presented successively in two spatially separated locations is perceived by listeners as smoothly moving from one location to the other²⁵. However, these effects seem to be observable only for a limited range of perceived velocities and interstimulus intervals. Grantham (1997) compared the perceptual effects of a sound source moving between points A and B and the same sound source appearing at point A and after a corresponding delay at point B. He observed that at a velocity of 20°/s, listeners could differentiate both conditions and inferred that the snapshot theory was not adequate to explain listeners' performance. He concluded that "if there is a specialized mechanism in the auditory system sensitive to horizontal motion, it apparently operates only in a restricted range of velocities" (Grantham, 1997, p. 295). It is, therefore, very likely that both of the proposed mechanisms of motion perception may exist, but that they operate in different velocity ranges.

From the practical standpoint, an important question is whether a person hearing a moving sound source can determine the distance to the source. Several studies have addressed this issue (e.g., Rosenblum et al., 1993; Schiff and Oldak, 1990), but since this is actually a distance perception question, it will only be mentioned here. According to Caelli and Porter (1980), in real-life situations people overestimate the distance to an approaching sound source by approximately a factor of two. In their study, listeners did not react to the sound of an ambulance siren until the ambulance was less than 100 m away. This may partially be explained by the *loudness constancy hypothesis*, according to which people do not pay attention to changes in loudness that

²⁵This effect is called auditory saltation.

result from a change in the distance between them and the sound source (e.g., Zahorik and Wightman, 2001).

Sound source localization is not only dependent on the position and movement of the sound source itself but also on the movement of the listener. The results of several studies indicate that slow, passive whole-body rotations improve rather than degrade localization accuracy (Perrett and Noble, 1997b; Thurlow and Runge, 1967). This finding is in agreement with the notion discussed in section 2 that small head movements of the listener improve localization accuracy. In contrast, transcutaneous vibrations applied to the posterior neck muscles cause systematic error (CE) toward the side of the vibrations (Lewald et al., 1999). Similarly, fast and extensive whole-body rotations lead to large CEs in the direction opposite to the direction of rotation (e.g., Jongkees and Van der Veer, 1958; Lester and Morant, 1970; Pierce, 1901). However, immediately after the termination of rotation, this systematic shift in perceived location changes to be in the direction of the former movement (e.g., Münsterberg and Pierce, 1894). Both these types of changes are analogous to the auditory motion aftereffect mentioned in section 5. They also suggest “that vestibular information is taken into account by the brain for accurate localization of stationary sound sources during natural head and body motion” (Lewald and Karnath, 2001).

15. Summary and Conclusions

The simple act of auditory localization has been the object of numerous studies that have produced a wealth of information about the physical, physiological, and psychological conditions that affect the accuracy and precision of localization. The overall purpose of this report was to summarize our basic knowledge about the auditory localization process and discuss various types of localization tasks, measures of localization accuracy and precision, and treatments of reversal errors in order to facilitate effective and uniform collection, processing, and interpretation of sound localization data. Both the processing and interpretation of localization data becomes more intuitive and simpler when the $\pm 180^\circ$ scale is used for data representation instead of the 0° – 360° scale, although the 0° – 360° scale can also be successfully used with caution. One of the main problems with analyzing localization data is a lack of clarity regarding various LE metrics. To guide in the selection of appropriate metrics, both linear and circular statistical analyses of localization data were described, various metrics compared, and their advantages and limitations stated. It has been explained that the standard statistical measures for assessing constant and random error are not robust measures, as they are quite susceptible to being overly influenced by extreme values in the data set. The robust measures discussed in this report are intended to provide researchers with alternative measures that may be beneficial for analyzing small-sample and unusual data distributions. Another aspect of data analysis stressed in this report was the importance of the separate processing of local (natural) localization errors and all reversal errors

(e.g., front-back errors). The sole use of overall LE metrics that combine CE and RE has been discouraged as has the uniform treatment of local errors together with reversal errors. Both these practices can lead to improper conclusions.

As stated at the beginning of this report its goal is to be a comprehensive review of auditory localization concepts, metrics, and basic findings. “Research on human sound localization is technically demanding” (Wightman and Kistler, 1993, p. 174) and a good understanding of underlying principles and methodologies is important for designing studies that measure what they are supposed to measure. However, this report is not intended to be a detailed guide for how to set up and run auditory localization studies since specific goals and technical constraints may dictate various methodological approaches. In this respect, the basic set of rules formulated at the beginning of 20th century by Angell (1903) still seems to provide valid, initial guidance:

1. A variety of different sound sources (sounds) should be used.
2. Sound sources should produce sounds of controllable intensity.
3. The listener should not know the actual locations of the sound sources.
4. All sound sources should be placed at equal distances from the listener.
5. There should be absolutely no reflected sounds arriving at the listener.²⁶
6. The listeners should have symmetrical hearing.

Decisions such as the number of listeners/judgments, the number of reference directions, the type of sound sources (sounds), and listener instructions can vary enormously across studies, depending on their specific goals. Even categorical localization studies, which are discouraged for use in studying localization phenomena, can sometimes be appropriate when applied to comparative assessments of equipment or combined with directional speech recognition tasks. The crux of the matter is that in such cases researchers should select a sound source distribution and formulate the research question in such a way that categorical data may be easily converted into absolute localization data, if needed.

Our intent was to provide a stable terminological base; outline the judgment and metrics options; discuss applied spatial perception research topics (directional audiometry and the localization of multiple and moving sound sources); and provide estimates regarding expected data. Although a lot is known about the human ability to localize sound sources producing single, stationary signals, researchers are just beginning to explore spatially divided attention, spatial memory, the perception of dynamically changing spatial signals, and serial localization judgments. The

²⁶Gerzon (1971; 1974) observed that in the case of multichannel stereo recordings, the addition of a moderate level of uniformly distributed reverberation energy to the recording may sometimes aid in the localization of the recorded sound sources. This may be due to the masking effect of the reverberation energy over some low-level discrete reflections present in the listening space.

provided information is intended to guide researchers in selecting both the research issues and the analytical tools to use in documenting the investigated issues.

The only two strictly methodological issues addressed in this report are the selection of a direction pointing technique and the learning/practice effect in auditory localization. The preferred type of directional response and listener learning/practice effects are the two most debated elements of localization study methodology, and therefore, we felt compelled to provide the reader with background information to help them to make informed decisions in designing their studies. However, both of these topics are addressed outside of the main body of the report as appendices A and B, respectively.

16. References

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Appendix A. Direction Pointing

Beyond the nature of the sound sources (type, number, visibility), environment (space geometry, reflections, atmospheric conditions, etc.), and listeners themselves (type, number), another important factor affecting the properties and extent of LE is the methodology used for data collection. For example, in 3-D auditory localization, sounds can be presented by a fixed array of loudspeakers (e.g., Gilkey et al. 1995), an arc of loudspeakers that can be rotated around a fixed axis (either vertically or horizontally) (e.g., Makous and Middlebrooks, 1990; Wightman and Kistler, 1989b), loudspeakers mounted on rotating booms (e.g., Oldfield and Parker, 1984a; Otten, 2001), or as phantom sources in a 3-D virtual space presented through earphones (e.g., Vermiglio et al., 1998) (See also the discussion of this topic in section 12.) Other methodological decisions are related to the presence and type of background noise and distracters, listener instructions, and the inclusion of the dynamic localization cues.

One of the most debated procedural elements of absolute auditory localization studies is the selection of the listener's overt response, that is, the type of direction pointing. The type of direction pointing used in a study is generally accepted as a factor contributing to the magnitude of the LE, and localization researchers make efforts to minimize this effect through listener training and collecting supplementary data (usually in the visual domain) on the precision of the response mechanism itself. Localization discrimination and categorical localization studies are not subject to pointing-based localization error since they rely only on nominal or categorical responses. A list of common techniques for direction pointing used in absolute localization studies is presented in table A-1. All pointing techniques listed in the table A-1 can be generally classified as egocentric (body-referenced) or exocentric (externally referenced) depending on the selected point of reference in making directional decisions.

Table A-1. Main pointing techniques used in auditory localization studies.

ID	Technique	Publications (Examples)	Comments
A	Verbal estimation	Cook and Frank (1977) Wightman and Kistler (1989b) Wenzel et al. (1993) Abouchacra et al. (1998a) Vause and Grantham (1999)	Egocentric technique. Verbal estimation can be in degrees or in time expressed on analog clock scale (e.g., 3:30)
B	Head (nose) pointing	Makous and Middlebrooks (1990) Bronkhorst (1995) Carlile et al. (1997) Djelani et al. (2000) Ocklenburg et al. (2010) Majdak et al. (2010)	Egocentric technique. In some studies head tracking systems were used (e.g., Carlile et al., 1997).
C	Hand pointing	Thurlow and Runge (1967) Djelani et al. (2000) Zwiers et al (2001) Majdak et al. (2010)	Egocentric technique. In some studies 3-D infrared or electro-magnetic tracking systems were used (e.g., Zwiers et al., 2001).
D	Swivel pointer ^a	Ocklenburg et al. (2010) Lewald (1998)	Exocentric technique.
E	Gaze direction	Frens and van Opstal (1995) Yao and Peck (1997) Hofman and van Opstal (1998) Hofman et al. (1998)	Egocentric technique.
F	Laser (gun) pointing	Oldfield and Parker (1984a) Seeber (1997) Pedersen and Jorgensen (2005) Scharine (2005) Scharine (2009)	Egocentric technique. In some studies wooden or metal pointers were used; Oldfield and Parker (1984a) used a photographic recording system;
G	Sphere and stylus	Hartung (1995) Gilkey and Anderson (1995) Gilkey et al. (1995) Good and Gilkey (1996) Otten (2001)	Exocentric technique. God's Eye View Localization Point (GELP) technique; the size of the pointing error depends on the size of the sphere;
H	Tablet and stylus	Hammershoi and Sandvad (1994) Moller et al. (1996) Haferkorn and Schmid (1996)	Exocentric technique. In some studies paper drawings were used (e.g., Haferkorn and Schmid, 1996)
I	Loudspeaker on a boom	Sandel et al. (1955)	Egocentric technique. Loudspeaker emitting a reference signal is placed at the angle from which the sound source was perceived.
J	Azimuth table	Dobbins and Kindick (1967)	Exocentric technique. Rotating pointer mounted on a table.
K	Virtual pointer	Langendijk and Bronkhorst (1997) Langendijk and Bronkhorst (2002a) Pulkki and Hirvonen (2005)	Exocentric technique. Controlled by joystick-like device.

^aA mechanical pointer that can rotate around its fixed point of reference (e.g., midpoint).

Another classification of pointing techniques, proposed by Comalli and Altshuler (1980), divides them into four classes: (1) kinesthetic (e.g., pointing with a laser or by turning the head), (2) visual (e.g., referring to a map or to numbers located at various positions on a screen covering the sound sources, (3) auditory (e.g., loudspeaker on a boom), and verbal (e.g., estimating the angle or quadrant).

An early comparison of different direction indication techniques was performed by Bauer and Blackmer (1965), who compared aiming (aligning the head and eyes with the direction of pointing) with simple directional pointing and found no difference in accuracy. Wightman and Kistler (1989b) compared verbal responses using degree and clock (e.g., 7 o'clock) scales and likewise found no difference between the two methods. Gilkey et al. (1995) reported that the God's Eye View Localization Point (GELP) technique (see table 3), also known as the *Bochum Sphere* (Hartung, 1995), was equally accurate as verbal indications of direction ($MUE \leq 5^\circ$) but less accurate than head (nose) pointing. In addition, Langendijk and Bronkhorst (1997) reported an advantage for virtual pointer techniques (row K in table 3) over verbal reporting.

Carlile et al. (1997) compared several pointing techniques and concluded that head (nose) pointing was more accurate than verbal estimates or the use of a stylus with either a sphere or a tablet. Majdak et al. (2010) compared hand and head (nose) pointing and found similar localization performance for both methods for horizontal as well as vertical localization tasks. Razawi (2009) compared gaze (eye and head), head, and eye pointing and found gaze pointing to be more accurate than either head or eye pointing alone (p. vi). However, the CE associated with these pointing techniques seems to additionally depend on the handedness of the listener. Ocklenburg et al. (2010) compared the localization accuracy of left- and right-handed listeners with the use of head and hand pointing and found that listeners demonstrated a bias toward their non-preferred side with both pointing methods.

However, it needs to be stressed that auditory localization accuracy in both the horizontal and vertical directions is affected by eye position regardless of the pointing method. For example, Weerts and Thurlow (1971), Hartmann (1983b), and Kopinska and Harris (2003) observed a gaze-related CE of 2° – 3° toward the direction of gaze. Some other authors have reported shifts of similar magnitude but either in the opposite direction (Lewald, 1998) or inconsistently in both directions (Lewald, 1997; Razavi, 2009). Getzmann (2002) studied the effect of gaze direction on localization in the median plane and reported an average shift of 8.6° toward the direction of eccentric gaze. All these reports indicate that eye position affects the perceived location of the sound source and that this effect may be different depending on the experimental conditions. It may also be time-dependent (Razawi, 2009; Razawi et al., 2007). It is, therefore, important to control for eye position in studies of auditory spatial perception that are not based on gaze pointing (Cui et al., 2010). It is also important to realize that head-pointing may lead to erroneous results if long sounds are used in an azimuth localization task at elevations other than 0° . Head-pointing in the vertical direction during the listening task changes the listener's

listening plane. With a tilted head, the listener is pointing in an oblique plane that constitutes a new “horizontal” plane for the listener. This may be a different task than is actually intended.

Several authors have also pointed out that localization performance can be affected by memory. For example, in head or laser pointing, the listener first determines the location of the sound source and then turns around to indicate the remembered position. However, Makous and Middlebrooks (1990) argued that the response technique appears to have only a negligible effect on localization performance.

In summary, on the basis of the conducted comparisons and meta-analyses of localization studies (e.g., Djelani et al., 2000), it can be concluded that egocentric systems (pointing toward the sound source or verbally indicating its position) are generally more precise than exocentric systems (using a display screen, drawings on paper, a response sphere, etc.), especially for listeners with no or minimal experience in using the specific pointing system. The most precise technique seems to be the laser pointing technique. Seeber (1997), for example, reported errors on the order of only 0.2° for laser pointing, which seem to be an order of magnitude smaller than the errors reported for other methods. It seems that the laser beam provides important visual feedback to the listener leading to more accurate sound source localization (Razavi, 2009, p. 216).

Appendix B. Localization Training

Performance in perceptual tasks improves with practice, and this process is called perceptual learning. If this process is structured by providing some form of feedback or adapting instructions, it is frequently referred to as perceptual training, behavioral training, or perceptual skills development. Most studies of auditory learning/training have demonstrated a high plasticity of the human auditory system in performing a variety of discrimination tasks (Fahle and Poggio, 2002; Habib and Besson, 2009; Polley et al., 2006). The maximal sensitivity to sensory exposure exists during the early postnatal developmental period and gradually decreases with as the brain matures. However, certain internal rewiring of brain regions can be seen to occur even in older people (e.g., Spolidoro et al., 2009). A general discussion of spatial adaptation can be found in Welch (1986).

One aspect of audition that might be expected to be especially affected by sensory experience is spatial perception (King, 1999). Sound, unlike visual or tactile stimuli, has no specific location (Nudds, 2001; O'Shaughnessy, 2002, p. 446). Therefore, the brain has to determine where the location of the sound source on the basis of a variety of localization cues. Such a situation lends itself to gradual improvements in sound processing by the brain, resulting in improved auditory spatial perception. However the data provided by psychoacoustic studies to date do not present a clear picture of how repeated exposure to the same set of spatial situations affects a listener's general ability to localize sound sources.

The learning of auditory localization skills may be considered as the effect of practice (repetition without feedback) or training²⁷ (practice with feedback), and may involve natural or altered localization cues. Natural localization cues are the cues that a person has already been using, while altered cues arise when natural cues change due to asymmetrical hearing loss, pinna modification, the use of single hearing aid, etc.

The data reported in the literature regarding the effect of practice (no feedback) on absolute auditory localization with natural localization cues are contradictory. Several authors have reported no or insignificant practice effect (e.g., Davis and Stephens, 1974; Carlile et al., 1997; Giguère and Abel, 1993; Hartmann, 1983a; Russell, 1976; Savel, 2009; Zwiers et al. 2001; Zahorik et al., 2001; Zahorik et al. 2006). This finding seems to be independent of whether the listeners have or have not had previous training (e.g., Wersenyi, 2009; Zahorik et al., 2001). However, there are also some reports indicating that simple practice may have an effect on localization performance. For example, Jacobsen (1976) reported that the MAA threshold gradually improved from 1.7° at the beginning of data collection (first eight series) to 0.75° at

²⁷Unfortunately, the terms practice and training are frequently used in the literature interchangeably and practice without feedback or some form of guiding instructions is also frequently described as training.

the end of data collection (last eight series). Wright and Fitzgerald (2001) and Abel and Paik (2004) observed improved absolute localization performance with practice for high frequency sound sources (4 kHz; IIL cues) but not for low frequency sources (500 Hz, ITD cues). Minnaar et al. (2001) studied localization accuracy with binaural recordings made with several artificial heads and reported continuous improvement over a period of five days. Honda et al. (2007) reported that two weeks of game playing in an AVR substantially improved the players' AVR localization accuracy in both the horizontal and vertical planes. However, for studies demonstrating the effectiveness of practice on localization performance in AVR environments, the question arises as to what extent the observed improvements are the results of the practice itself and to what extent they are the effects of procedural learning and adaptation to the AVR environment (Hawkey et al. 2004). In addition, an increase in localization performance due to game playing cannot be considered a simple practice effects since game progress provides natural feedback to the player. Similarly, in some longer lasting practice studies, the listeners may receive unintentional behavioral or ecological feedback and learn where the actual sound sources are physically located.

In contrast to the unclear effect of simple practice, the majority of literature reports are in agreement that providing feedback-based or multimodal localization training prior to the auditory localization study is effective in reducing front-back errors and improving overall localization performance (e.g., Makous and Middlebrooks, 1990; Martin et al., 2001; Park, 1996; Pearce, 1937; Perrott et al., 1969; Wright and Zhang, 2006; 2009; Zahorik et al., 2006). For example, Zahorik et al. (2001) reported that visual feedback training markedly improved the localization accuracy of their listeners, with the improvement appearing to last for several days. Majdak et al. (2010) observed a large training effect (with feedback) for about the first 400 trials (3–4 h) of a sound localization task and a smaller improvement beyond those 400 trials. The accuracy and precision of the judgments increased, and the number of front-back errors decreased. In contrast, Terhune (1985) reported no benefit with feedback-supported short-term practice (50 trials).

Despite several accounts of effective adaptation to new sets of localization cues, the overall results of the reviewed studies lead to the conclusion that although adaptation to new localization cues is generally fully successful in the median plane, it is frequently only partially successful in the horizontal plane (e.g., Javer and Schwartz, 1995; Shinn-Cunningham et al., 1998a; Wright and Zhang, 2006). The complete or partial adaptation or re-adaptation process is asymptotic and has been reported to take about 7–14 days (e.g., McPartland et al., 1997; Van Wanrooij and Van Opstal, 2005), although some adaptation can already be observed within 1–2 h (e.g., Wright and Zhang, 2006). In contrast, other authors did not observe any adaptation effects in localization performance after 24 h (Slattery and Middlebrooks, 1994) or several days (McPartland et al., 1997) of continuous use of a unilateral earplug. In general, training is most effective if repeated every day and single-day training session has never been shown to have a lasting effect.

It is important to stress that many authors have reported very large individual differences in localization performance among listeners (e.g., Javer and Schwartz, 1995; Langford, 1994; Shinn-Cunningham et al., 1998a; Wenzel et al., 1993; Wright and Fitzgerald, 2001), leading to the concepts of *good localizer* and *poor localizer*. Some authors attribute this ability to specific anatomical differences in the shape and size of the head, pinna, and concha (e.g., Middlebrooks and Green, 1991; Wightman and Kistler, 1989b). Saberi and Antonio (2003) further noticed that poor localizers have a tendency to improve their localization performance with training while good localizers do not. These results seem to suggest that the difference between good and poor localizers is not only physiological but may also result from previous exposure to the variety of spatial environments and from lifestyle.

Although there is a lack of unequivocal evidence that people improve their localization abilities after short-term practice before or during the course of an experiment, there is little doubt that some long-term adaptation (on the order of days and weeks) takes place to altered localization cues. Long-term adaptation to new localization cues takes place continuously during a child's developmental as the size of the head gradually increases, but it can also occur in adulthood. Most people can adapt to unilateral hearing loss (Gardner and Gardner, 1973; Florentine, 1976; Nabelek et al. 1980) and hearing aids (see Byrne and Dirks [1996] for an overview) and re-learn to localize sound sources correctly after external ear surgery or other modification to their ears (e.g., Musicant and Butler, 1980; Butler, 1987; Oldfield and Parker, 1984b; Hofman et al. 1998; Shinn-Cunningham et al. 1998a). This adaptation to new cues seems to also apply to preprocessed cues that simulate larger-than-normal head size and make better-than-normal spatial resolution possible, which is of special interest to military researchers (e.g., Shinn-Cunningham and Durlach, 1994).

Shinn-Cunningham et al. (1998ab) studied the effect of synthesized supernormal localization cues on spatial perception. While supernormal localization cues can improve localization discrimination (see section 8), they cause a shift in the apparent location of the sound source simulated by the cues and may worsen the accuracy of absolute localization. The authors concluded that training reduced the size of absolute CE but also that the listeners never completely adapted to the new set of cues. Such incomplete adaptation is consistent with previous reports (e.g., Welch, 1986). Another observation made by the authors was that the listeners were “able to accommodate only linear transformations of cues, rather than being able to adapt to arbitrary complex remappings” (Shinn-Cunningham et al., 1998b, p. 3675).

Three additional comments need to be made with respect to adapting to altered localization cues:

1. It seems that the adaptation process cannot be generalized to stimuli that are very different from those used in the practice/training (Feinstein, 1973; Butler, 1987).
2. Adaptation seems to be asymmetrical and is greater in the left than the right hemifield (Wells and Ross, 1980; Shinn-Cunningham et al., 1998a; Savel, 2009).

3. The available data (e.g., Kumpik et al., 2010; Nabelek et al., 1980) indicate that people can quickly re-learn natural localization cues after the cause of the altered cues has been removed, indicating that the natural neural traces in the brain are not significantly altered by learning the new cues.

In addition, it is noteworthy that people are completely unable to adapt to the reversal of left and right ear cues (Young, 1928; Hofman et al., 2002).

The same capacity for plasticity in auditory localization described earlier for adult humans has also been reported for other animals (e.g., Knudsen et al., 1984; Knudsen, 1984; 1985; King et al., 2011). In addition, both human and animal studies indicate that brain wiring cannot be changed without previous normal binaural experience (e.g., Knudsen, 1985; King and Carlile, 1993). For example, Wilmington et al. (1994) reported that the surgical correction of congenital unilateral hearing loss did not restore normal binaural hearing. Even a long time after the surgery, the spatial auditory capabilities that require the integration of basic binaural cues had not been restored. Together these findings support the notion that the neural mechanisms underlying auditory spatial perception are dependent on initial auditory exposure for proper development (Mrsic-Flogel et al., 2001). In addition, animal studies indicate that the duration of the after-effect resulting from the removal of a monaural earplug seems to be species dependent (King et al., 2011).

One difficulty with comparing the effects of practice and training on localization performance reported in various studies is that most reports provide qualitative or raw quantitative data without any formal data analysis. In addition, these effects are normally discussed for overall LE without separate considerations for CE and RE. A simple method of determining the effect of training on the size of RE is to use a variant of Fisher's F-test (variance ratio test) (Fisher, 1920), that is, by calculating the ratio of the data variances before and after training

$$F = \frac{v_{prior}}{v_{post}} = \frac{SD_{prior}^2}{SD_{post}^2}, \quad (49)$$

where v_{prior} , v_{post} , SD_{prior} , and SD_{post} are, respectively, the variances and standard deviations of the data collected in the localization test before and after training. Alternatively, any other similar test of equality for two variances can be used (see any standard statistical software package or textbook).

A convenient measure of the effect of practice or short-term training on CE is Cohen's d defined as

$$d = \frac{x_{prior} - x_{post}}{SD}, \quad (50)$$

where x_{prior} and x_{post} are the arithmetic means of the judgments made prior to and after training and SD is the pooled standard deviation calculated as

$$SD = \sqrt{\frac{(n-1)(SD_{prior}^2 + SD_{post}^2)}{2n}}, \quad (51)$$

where SD_{prior} and SD_{post} have the same meaning as in equation 48 and n is the number of judgments made by the listener. Cohen's d is a measure of *effect size*, and by convention, an effect size of ± 0.2 is small, ± 0.5 is moderate, and ± 0.8 or greater is large (Cohen 1988; 1992). Note that Cohen's d may be larger than 1. A good tutorial on the use of various measures of effect size is provided by Thalheimer and Cook (2002).

A good summary of the effects of practice, training, and adaptation on sound source localization is available in Wright and Zhang (2006). They concluded that although human adaptation to altered sound localization cues, either complete or partial, has been well established, the evidence of a practice effect is unclear.

Finally, Durlach and Pang (1986) and Rabinowitz et al. (1993) showed that the proper frequency scaling of an individual's HRTF (and the distance to the sound source) can produce HRTFs for a similar but larger head size and result in improved localization resolution. Another type of HRTF manipulation that preserves the same ITDs and IIDs but reassigns them to different angles of sound arrival was described by Durlach et al. (1993). Such transformation can increase spatial resolution in the frontal direction but decrease it along the interaural axis

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
AAM	apparent auditory motion
AES	anterior ectosylvian sulcus
ALF	Auditory Localization Facility
AMA	auditory motion aftereffect
AN	auditory nerve
ANSI	American National Standards Institute
APA	American Psychology Association
ARL	U.S. Army Research Laboratory
ASA	auditory scene analysis
AVR	auditory virtual reality
BF	back-front
CC	corpus callosum
CE	constant error
CMAA	concurrent minimum audible angle
CMR	Coordinated Measure Response
CN	cochlear nucleus
CNS	central nervous system
CRT	Choice Reaction Time
DCN	dorsal cochlear nucleus
DDT	directional detection threshold
DL	difference limen
DOA	direction of arrival

EE	excitatory-excitatory
EI	excitatory-inhibitory
FB	front-back
GELP	God's Eye Localization Viewing
GoF	goodness-of-fit
HMR	head movement response
HRTF	head-related transfer function
IC	inferior colliculus
IED	interaural envelope difference
IID	interaural intensity difference
IPD	interaural phase difference
ISD	interaural spectrum difference
ISI	Interstimulus Interval
ITD	interaural time difference
KEMAR	Knowles Electronic Manikin for Acoustic Research
LE	localization error
LGoF	localization goodness of fit
LL	lateral lemniscus
LSO	lateral superior olivary
MAA	minimum audible angle
MAD	mean absolute deviation
MAMA	mean audible moving angle
MD	median
ME	mean (signed) error
MEAD	median absolute deviation
MGB	medial geniculate body
MSO	medial superior olivary

MUE	mean unsigned (absolute) error
RE	random error
RMSE	root-mean-squared error
S	skew
SAINT	Source Azimuth Identification in Noise Test
SC	superior colliculus
SD	standard deviation
SE	standard error
SEK	standard error of kurtosis
SES	standard error of skew
SF	Fisher's skew
SL	sensation level
SNR	signal-to-noise ratio
SOA	stimulus onset asynchrony
SOC	superior olivary complex
SP	Parson's skew
SRT	simple reaction time
TB	trapezoid body
TCAPSs	tactical communication and protection systems
VCN	ventral cochlear nucleus
VE	ventriloquism effect
WWM	Wheeler-Watson-Mardia

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